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A GOLD–SCHEELITE–CINNABAR PLACER IN HUMBOLDT COUNTY, NEVADA[1]

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ABSTRACT

Gold, scheelite, and cinnabar in amounts that might be profitably extracted are found in a placer deposit in the Dutch Flat mining district in north-central Nevada. These materials are the products of at least two and possibly three stages of metallogenic activity recorded in the district. The gold and perhaps most of the scheelite were derived from quartz veins that cut a small granodiorite stock and lower Paleozoic sedimentary rocks. Part of the scheelite may have been derived from contact-metamorphic deposits associated with the granodiorite stock. The cinnabar came from a shear zone that is later than the quartz veins. The proximity of the placer to the source of the minerals is the factor that made a significant concentration of these minerals possible. Incomplete sampling of the placer indicates an average value of $1.50 per cubic yard in combined gold, tungsten, and mercury based on the price of these metals in August 1954.

INTRODUCTION AND ACKNOWLEDGMENTS

SIGNIFICANT amounts of gold, scheelite, and cinnabar are present in a placer deposit in the Dutch Flat mining district, on the west slope of the southern end of the Hot Springs Range, Humbolt County, Nev. (Fig. 1). The district

[1] Publication authorized by the Director, U. S. Geological Survey. Presented before the Geological Society of America, Berkeley meeting, April 1955, under the title "A tri-metal placer in north-central Nevada."

is about 18 miles northeast of Winnemucca and 14 miles north of Golconda and consists of 20 lode claims and 160 acres of placer gravels wholly owned by Dutch Flat Mines, Inc. The claims are explored by 10 small mines with an aggregate of 4,000 feet of underground workings, and in addition many shallow prospect pits and short adits.

The district has a semiarid climate with a mean annual precipitation of about 6 inches, most of which occurs as snow in the winter and early spring. Springs are found in most of the canyons, but their flows are small and in all

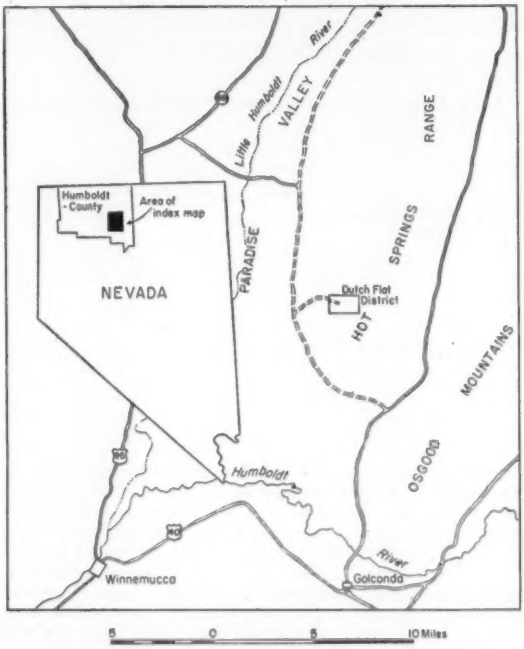


FIG. 1. Index map showing location of Dutch Flat district, Nevada.

but the wettest years most springs dry up in late summer. An adequate supply of water for mining operations, however, can be pumped from wells in Paradise Valley, about 3 miles west of the district.

The information presented here has been collected intermittently since 1952, in the course of mapping the Osgood Mountains quadrangle, Nev., by the U. S. Geological Survey.

The writers are indebted to T. A. Cowan, President, and M. G. White, Secretary-Treasurer, of Dutch Flat Mines, Inc., and Don B. Sebastian for assay data and other helpful information. H. G. Ferguson, R. G. Yates, D. C.

Arnold, and E. H. Pampeyan of the U. S. Geological Survey critically read the manuscript and made many helpful suggestions.

HISTORY AND PRODUCTION

Placer gold was discovered in the area by F. G. Wendell in 1893 (7), and most of the mines and prospects are probably the result of subsequent search for lode deposits. Cinnabar was probably noted in the early placer operations, but it was not discovered in place until 1939. The present Dutch Flat mine was developed on this cinnabar showing. The original discovery of scheelite is unknown, but scheelite was recovered along with cinnabar and gold in the operation of a small washing plant in 1952.

The only published production figures available for the district are those given by Vanderburg (7) and Smith and Vanderburg (6) for placer gold production, and those given by Bailey and Phoenix (1) for lode quicksilver. Gold production in the first year after discovery amounted to about $75,000; and Vanderburg states that the total placer gold production in the district has been worth about $200,000, nearly all of which was recovered by working with rockers (7). According to Bailey and Phoenix (1), the Dutch Flat mine produced 70 flasks of mercury to the end of 1942. Mercury production since the end of 1942 has amounted to less than 2 flasks a year from the Dutch Flat mine.[2]

GEOLOGY

Folded sedimentary rocks of early Paleozoic age, a small intrusive igneous body of uncertain age, Tertiary volcanic rocks, and Tertiary and Quaternary gravels occur in the district. Figure 2 shows the general geologic setting of the district.

The sedimentary rocks consist of feldspathic graywacke and feldspathic quartzite,[3] feldspathic pebble conglomerate, shale, and calcareous shale of the Harmony formation. The Harmony formation has been tentatively assigned a Mississippian age by Ferguson and others (2), but recent work in the Osgood Mountains quadrangle by the authors (3) indicates that the formation is at least in part Late Cambrian.

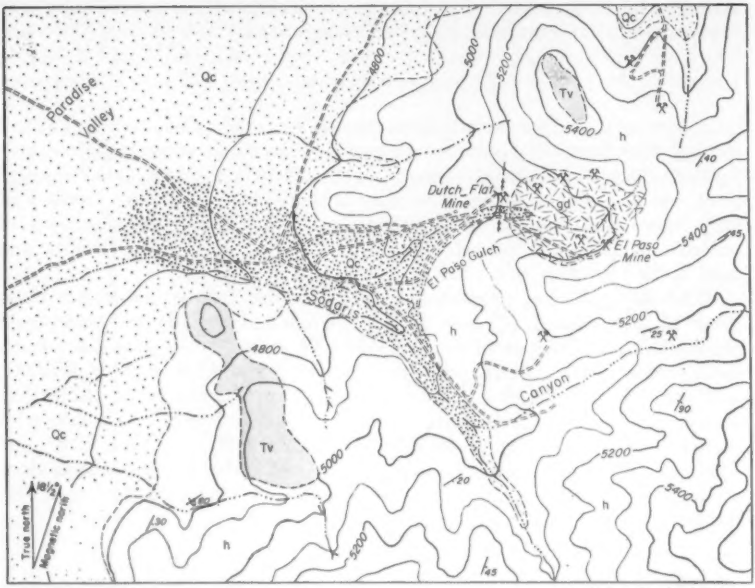
These sedimentary rocks have been strongly folded into a series of recumbent folds. The major folds are all overturned to the west, but some smaller folds are overturned to the east.

The Harmony formation has been intruded by a small granodiorite stock, which has produced an irregular contact-metamorphic aureole extending for a maximum distance of about 500 feet. Shale and calcareous shale have been converted to hornfels, and the sandstone and grit beds show local silicification and induration.

Basaltic andesite of Tertiary age overlies the Harmony formation with an

[2] Data furnished by Dutch Flat Mines, Inc. Published with permission.

[3] Following Pettijohn (5, p. 363–364), feldspathic graywacke is a rock containing 15 percent or more detrital matrix and a sand fraction more than 25 percent of which consists of unstable particles with feldspar predominating; feldspathic quartzite is similar but contains less than 15 percent detrital matrix and a smaller proportion of unstable components.



Geology by Preston E. Hotz and Ronald Willden, U.S.G.S., 1953
Cartography by R. Duggin

2000 0 2000 4000 Feet

Contour interval 100 feet
Datum is mean sea level

EXPLANATION

QUATERNARY

Qc — Cover and alluvium
Heavier shading indicates area most likely to contain profitable concentrations of placer materials.

TERTIARY

Tv — Volcanic rocks
Basalt to basaltic andesite in composition

Tgd — Granodiorite

h — Harmony formation
Largely sandstone and shale. Early Paleozoic

Contact, approximately located

Shear zone, containing disseminated cinnabar

Strike and dip of beds

Strike and dip of overturned beds

Strike of vertical beds

Mine or prospect

FIG. 2. Geological map of Dutch Flat placer and vicinity.

angular unconformity. The basaltic andesite is evidently younger than the granodiorite stock because the basaltic andesite shows no effect of the metamorphism that accompanied the igneous intrusion or the hydrothermal alteration believed to be a late stage of the intrusive activity.

Unconsolidated gravels of two different ages are found within the area. The oldest gravel occurs as isolated patches—too small to be shown on the geologic map—resting on the Harmony formation and overlain in places by basaltic andesite. It consists of well-rounded pebbles, cobbles, and boulders of Harmony conglomerate and graywacke; and clean, fine-grained quartzite, unlike any rock that is exposed in the area. The gravel represents channel fillings of a pre-basaltic andesite drainage system. These gravels have been extensively prospected for placer gold, but no values in gold have as yet been reported. The younger gravels occur in the bottoms of the canyons, on the alluvial fans, and as slope wash on the sides of the canyons. They consist of rounded pebbles, cobbles, and boulders of basaltic andesite, granodiorite, and rocks derived from the Harmony formation.

LODE DEPOSITS

Two types of lode deposits of two ages are present in the area, and the existence of a third type is inferred. The oldest consists of two sets of quartz veins that contain minor amounts of gold and base metal sulphides. The youngest type is disseminated cinnabar in a shear zone that is younger than the quartz veins. Contact metamorphic rocks containing scheelite may be present in the area, but such deposits were not observed during the field work, and the only known evidence of their existence is the scheelite and garnet in the placer.

The quartz veins are too low grade to be worked at a profit, but they are of interest because they have supplied gold and possibly scheelite to the placer. The quartz veins occupy two northeast-striking fault systems: one, in the granodiorite stock, dips about 30° northwest and another, in the sedimentary rocks, dips steeply from northwest to southeast. The veins are generally from 3 inches to 2 feet thick, but veins as much as 8 feet thick have been observed. Some veins exposed in the mine workings give assay values in gold ranging from 0.01 to 0.05 ounces per ton and in silver ranging from 0.3 to 1.5 ounces per ton.[4] Free gold was observed in quartz from a small prospect hole just north of the mouth of Sodaris Canyon, and T. A. Cowan, President of the Dutch Flat Mines, Inc. (personal communication), reports that pockets of ore running $200 in gold per 50-pound ore sack were encountered in the El Paso mine. Galena, sphalerite, chalcopyrite, pyrite, and jamesonite have been identified in some vein quartz. Small amounts of scheelite were observed in two of the quartz veins, and small pebbles of quartz containing scheelite have been found in the slope-wash gravels.

Cinnabar is found disseminated in a shear zone in metamorphosed shale and feldspathic quartzite of the Harmony formation just west of the granodi-

[4] Assays for the authors by Union Assay Office, Inc., Salt Lake City, Utah.

orite stock. The shear zone strikes about N 10° E, dips from 20° to 35° SE, and has an average width of about 5 feet over a length of 900 feet. Brecciated quartz containing sulphides is found in the shear zone, and for this reason the shear zone is regarded as being younger than the quartz veins. Cinnabar is disseminated throughout the shear zone and locally in the undisturbed sedimentary rocks on either side of the shear zone; but it can be profitably mined only from irregular shoots, which have a maximum width of about 2½ feet. The average grade of the mined material was about 20 pounds of mercury per ton (1).

PLACER DEPOSITS

Two types of placer deposits are present in the area: stream deposits containing water-transported material, and slope-wash deposits containing material weathered from rocks in the immediate vicinity. The stream-transported material occurs in the bottoms of the larger canyons and on the alluvial fan below the mouth of Sodaris Canyon (Fig. 2). The stream deposits range in depth from 10 feet in the upper parts of the canyons to 35 feet at the mouth of Sodaris Canyon, with an average depth of about 20 feet. The depth of the alluvial fan below the mouth of the canyon is known from a few scattered prospect pits to range from 12 to 90 feet.

The slope-wash deposits are found on both sides of El Paso Gulch to a height of as much as 50 feet above the creek bottom. The slope-wash deposits, as the term is used here, include some stream-transported material which was left on the sides of the canyons as the streams cut down through bedrock. Some high assays reported from the slope-wash material are probably due to such accumulation of placer material from the stream channels. The slope-wash deposits range in depth from 5 to about 25 feet, with an average vertical depth to bedrock of 12 feet.

Grade.—Sampling of the placer deposits has been sporadic and in general inadequate to delimit channels or pay streaks. Smith and Vanderburg (6) report that the placer covers an area 8,000 feet long and 300 to 2,000 feet wide. Twenty acres of this ground sampled in 1904 (7) gave an average value in gold of 31 cents per cubic yard based on a price of $20.67 per ounce. Assays of the placer material supplied by the Dutch Flat Mines, Inc.,[5] give values of gold ranging from 20 cents to more than $1.00 per yard, mercury ranging from 12 to 60 cents per yard based on the price of mercury in March 1954 ($185.00 per flask), and scheelite ranging from 60 cents to $2.00 per yard based on a price of $39.00 per 20-pound unit of WO_3. Don B. Sebastian of San Francisco, Calif., has the property under lease. His preliminary samples of the alluvial fan and lower stream gravels, covering an area of about 50,000 square yards, indicate an average grade of $1.50 in combined gold, mercury, and tungsten based on the prices of the metals in August 1954 (mercury at $290.00 per flask) and a 60 percent WO_3 concentrate. Values up to $30.00 per yard for some of the slope-wash material have been reported, but such high values are probably a result of nuggets salting the sample.

[5] Published with permission of the owners.

Minerals in the Placer and Their Source.—The gold in the placer occurs as coarse angular grains, which are sometimes attached to a quartz matrix, and as fine angular free grains. Smith and Vanderburg (6) report that the purity of the gold is 940 fine, and Vanderburg (7) states that the largest nugget found had a value of $180. A sample of gold from concentrates of slope-wash material assayed by C. W. Hammond (personal communication) of the Nevada Mining Analytical Laboratory was 954 fine. The samples of placer material from the fan that were examined contained no gold, so no information on the change in size or angularity of the gold nuggets and grains with distance of transport is available. The maximum distance of transport is less than 2 miles, and it seems unlikely that the gold particles would decrease very much in grain size in such a short distance. All the quartz veins assayed contained some gold, and this fact, together with the reported occurrence of rich pockets of ore in some of the mines, indicates that there is an adequate source within the district for the gold in the placer.

The scheelite occurs as nearly equant grains that range in size from 0.05 mm to 1 cm. The larger grains are found in the slope-wash material from the sides of El Paso Gulch and from stream deposits in El Paso Gulch above the junction with Sodaris Canyon. Scheelite grains in samples of the upper part of the alluvial fan rarely exceed 1 mm in size, and their average size is about 0.5 mm. The scheelite fluoresces blue-white and is presumed to be free of molybdenum.

Some of the scheelite is combined with quartz, particularly that in the slope-wash material. This association is regarded as an indication that at least part of the scheelite was derived from erosion of the quartz veins, even though the quartz veins exposed in the mine workings carry very little scheeelite. An undiscovered source of at least part of the scheelite may exist in the district. Calcareous shale and sandy limestone beds occur in the Harmony formation in the area, and it is possible that contact-metamorphic tungsten deposits in these calcareous beds were the source of part of the scheelite in the placer. The small amount of garnet associated with scheelite in the placer lends some support to this idea, but no contact-metamorphic tungsten deposits are exposed in the area.

The cinnabar grains range in size from minute dust to nuggets about 1 cm in diameter. The larger grains are not single crystals of cinnabar but consist of aggregates of cinnabar, quartz, and feldspar. The cinnabar commonly makes up 70 to 80 percent by volume of the aggregates. The cinnabar shows a closer correlation of grain size with distance of transport than either the scheelite or gold. The larger grains are found only in the upper part of El Paso Gulch, whereas the material from the alluvial fan is rarely larger than 0.5 mm and is generally very fine grained, with average grain size smaller than 0.02 mm. The shear zone containing cinnabar provides an adequate source for the cinnabar found in the placer.

A number of valueless heavy minerals are associated with the gold, scheelite, and cinnabar, especially in the fine size fractions of the placer concentrates. The principal heavy minerals are magnetite, ilmenite, hematite, zircon, and pyrite, with relatively minor amounts of hornblende, monazite, garnet, and

augite. In a process that will recover the scheelite and cinnabar, in addition to the gold, these heavy minerals will have to be considered. These heavy minerals are scarce in the size fractions of concentrates larger than about 1 mm, but they become increasingly abundant in the fine-size fractions, until in the size fraction smaller than 0.1 mm, only 25 percent of the total heavy minerals consist of gold, scheelite, and cinnabar.

CONCLUSIONS

The concentration of the minerals is largely due to the proximity of the placer deposits to the source of the placer minerals. Greater distance of transportation of the minerals would result in progressive loss of cinnabar and, to a lesser extent, scheelite due to comminution of these brittle minerals by abrasive action in the stream. This effect is demonstrated by samples of concentrates from the slope-wash materials and samples from test pits on the alluvial fan. The average grain size of scheelite in the slope-wash material is 3 mm, and the average grain size is reduced to 0.5 mm in material from test pits on the upper part of the fan. The average grain size of the cinnabar decreases from 0.5 mm in material from the upper part of El Paso Gulch to less than 0.02 mm in material from the upper part of the alluvial fan.

Profitable exploitation of the placer depends on an adequate supply of water and a milling technique that will permit the recovery of the gold, scheelite, and cinnabar at a reasonable cost. Water can be pumped from wells in Paradise Valley 3 miles to the west, where a ground-water study indicates that an annual supply of about 15,000 acre-feet of water is available for pumping (4, p. 52). The entire flow of the Little Humboldt River, which flows through Paradise Valley, is diverted for irrigation purposes during much of the year and cannot be relied on as a source of water. Separation of the valuable minerals from a heavy-mineral concentrate might be accomplished by amalgamating the gold, then furnacing the concentrates to recover the mercury, and finally floating the scheelite to yield a high-tungsten concentrate.

U. S. GEOLOGICAL SURVEY,
MENLO PARK, CALIF.,
May 24, 1955

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SALT–WATER ENCROACHMENT AS INDUCED BY SEA–LEVEL EXCAVATION ON ANGAUR ISLAND[1]

CHESTER K. WENTWORTH, ARNOLD C. MASON, AND DAN A. DAVIS

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ABSTRACT

Angaur, southwesternmost of the Palau Islands, 800 miles southwest of Guam, has an area of 3.2 square miles and consists of reef limestone of Pliocene through Recent age. In the northwestern part of the island a basin is formed by a ringlike ridge that has a maximum altitude of 150 feet. To the east and south a series of arc-shaped lower ridges and intervening depressions are concentric with the ring ridge. Beyond these, a low plain with shallow swales composes the remaining two-thirds of the island. The ridges are composed of indurated limestone, whereas the plain is underlain chiefly by unconsolidated coralline fragments.

Phosphate has been mined from the three types of topographic depressions since 1908. When power equipment was introduced, excavations were extended below sea level. Lakes formed in these excavations and, despite an annual rainfall of 110 inches, contamination of fresh-water supplies and of agricultural land by salt water resulted from tidal pulsations through the fissured rock. As a result, stoppage of mining was imminent unless remedial measures could be devised.

Angaur provides a model of the operations of a Ghyben-Herzberg fresh-water lens on an oceanic island. At numerous lakes, wells, and test holes, continuing observations were made on water levels; amplitude and lag of tidal fluctuations; and mineral content, pH, and temperature of the lens. These observations guided the selection of constantly adjusted remedial measures, which included partitioning of lakes, and bottom filling or back filling of compartments that failed to freshen because of fissures connecting them with the sea.

INTRODUCTION

ANGAUR (6°54′ N, 134°09′ E) is the southwesternmost of the Palau Islands, which are 800 miles southwest of Guam in the western Caroline Islands. It has an area of 3.2 square miles. Phosphate has been mined from open pits

[1] Publication authorized by the Director, U. S. Geological Survey.

since the discovery of the deposits by the Germans in 1908, except for brief periods in World War I and World War II. Along with Peleliu, 8 miles to the northeast, the island was invaded by United States military forces in September, 1944, just prior to the attack on the Philippine Islands.

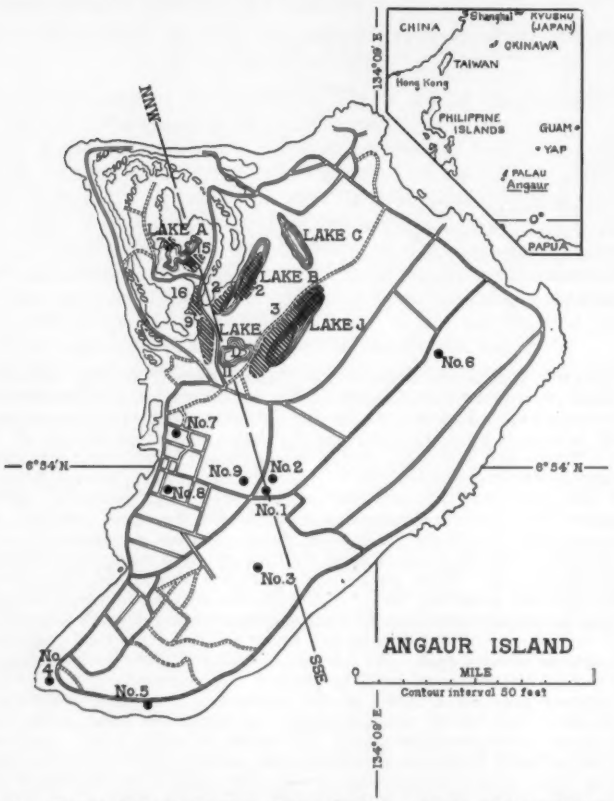

FIG. 1. Sketch map of Angaur, Palau Islands. Areas considered for mining authorization are shaded diagonally and numbered. Lakes resulting from previous excavations for phosphate are lettered. Wells are shown by numbered dots. The drying plant and loading installations are in the area north of well No. 7. Dashed line locates cross section of Figure 2.

When power equipment was introduced by the Japanese in 1938, excavations produced in the removal of phosphate were extended below sea level. Lakes formed in these excavations and, despite an average rainfall of 110 inches, contamination of fresh-water supplies and of agricultural land by salt water resulted from the effect of tidal pulsations acting through the

subterranean interconnections of the lakes with the sea. As a result, stoppage of mining was imminent unless remedial measures could be devised.

The writers undertook the survey of Angaur as a team, appointed by agreement between Headquarters, Supreme Commander for the Allied Powers, Tokyo, which had authorized postwar resumption of mining by the Japanese, and the Office of the High Commissioner of the Trust Territory of the Pacific Islands. The writers were directed to evaluate the reported damage to ground water and to agricultural land, and if possible to suggest a method of repairing some or all of the damage. A report of specific findings and recommendations has been presented officially.

GEOLOGY OF ANGAUR

Angaur is roughly triangular in shape (Fig. 1). The northwest third of the island is composed chiefly of Palau limestone, which in general is an indurated reef rock of Pliocene and Pleistocene age. The surface of this part

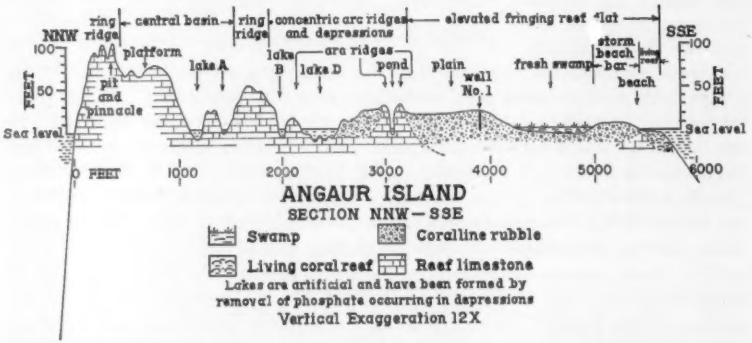

FIG. 2. Cross section of Angaur. The fissured limestone in the northwest contrasts with the coralline rubble in the southeast, forming two distinct groundwater provinces. The levels of the lakes average slightly less than 2 feet above mean sea level. Section is located in Figure 1.

of the island is generally rough and has many solution pits and pinnacles. The highest part is a ringlike elliptical ridge that has a maximum altitude of 150 feet. The ring ridge encloses a central basin within which is a small artificial lake (Lake A in Fig. 1), the surface of which is nearly 2 feet above sea level (Fig. 2). To the east, southeast, and south of the ring ridge and concentric with it is a series of lower arcuate ridges and intervening depressions that contain other artificial lakes (B, C, D and J in Fig. 1). The ridges and depressions are underlain by the Peleliu limestone of Pleistocene age.

Beyond these, a low plain with shallow swales composes the remaining two-thirds of the island. The plain slopes slightly from the northeast, where it has an altitude of about 20 feet, to the southwest, where the altitude ranges from about 10 feet to less than 5 feet. The plain is directly underlain for the most part by coralline rubble in the northeast and by beach deposits in the

southwest, except for the part less than 5 feet in altitude where there are swamp deposits. These deposits are all of recent age. It is probable that they lie on a platform of limestone at shallow depth. It appears that the ring ridge was the first reef development on an unrevealed volcanic foundation; the concentric ridges were successive reefs that grew on a shallow side; and the plain is an elevated fringing reef flat.

In the central basin, in the depressions between the arcuate ridges, and in swales on the plain, leachings from guano have replaced limestone and formed phosphate deposits. On and near the surface the deposits commonly consist of scattered brown nodules emplaced within or weathered out of the limestone, or of brown oölites occurring as a thin covering or as the filling of solution pits. The bulk of the ore, however, occurs below the water table and consists of blanket deposits of white non-indurated fine grains of calcium phosphate having a thickness ranging from 5 to 65 feet. This type of deposit has a very irregular bottom and is commonly underlain by a few feet of impure rock phosphate that grades into limestone.

GROUND-WATER GEOLOGY

Angaur may be divided into two contrasting ground-water provinces: the rough, hilly northwestern area underlain chiefly by limestone; and the plain to the southeast underlain chiefly by unconsolidated coralline deposits. In the limestone of the northwestern area, joints, fissures, and caverns that extend below sea level are numerous. The various channels provided by these openings allow relatively free movement of water and consequently conditions are unfavorable to the development of a Ghyben-Herzberg lens. Excavations made during the course of open-pit mining would tend further to interconnect these channels and counter the development of a lens. Samples of water from the various lakes produced by mining operations show an admixture of sea water. There are no data to indicate conditions of the ground water in the northwestern area prior to the commencement of mining in 1908, and it is not certain that a fresh-water lens existed at that time. However, it is apparent from the data gathered and from the testimony of the people of Angaur that the salinity of some of the lakes has been increasing.

The unconsolidated or poorly consolidated accumulations of coralline rubble and sand underlying the plain in the eastern, southeastern, and southern parts of Angaur form porous and permeable deposits containing few or no large fissures or caverns. Although probably at a depth of about 50 to 100 feet they rest on limestone, these deposits have a structure that is favorable for the formation of a Ghyben-Herzberg lens (2). Samples of water taken from a number of wells at various points on the plain, as well as the altitude of the water table at the wells, indicate the presence of a well-developed, relatively stable Ghyben-Herzberg lens in this part of the island. The rainfall maintains the lens with its top surface slightly more than 2 feet above mean sea level. There is no indication from the available information of any recent change in this condition.

ELEMENTS OF THE HYDROLOGIC MODEL

Assume as a hydrologic model a low oceanic island composed of homogeneous, loosely fragmental material sufficiently permeable that an annual rainfall of 110 inches is absorbed without runoff and the ground-water increment is discharged by the formation of a watertable mound having a height in general about 2 feet above mean sea level. Allowing 20 inches for evaporation and transpiration, the ground-water discharge may approximate 90 inches annually or about 0.02 foot daily (equals 0.1 foot in rock having a specific yield of 20 percent). With this much rainfall, reasonably well distributed throughout the year, the fresh-water lens that develops would displace salt water beneath the island to some tens of feet below sea level to form a balanced Ghyben-Herzberg lens.

The total apparent difference in head between the lens and sea level is usually composed of two elements: pressures that are in over-all balance, and pressures that are unbalanced. The first is caused by the difference in density between the fresh and sea water. Sea water is about $\frac{1}{40}$ denser than fresh water. At the base of the fresh-water lens the static hydraulic pressures are balanced and cause no movement. Above the base, although absolute pressures decrease, the pressure within the fresh-water column increases slightly but regularly upward with respect to that at the same horizon in the salt-water column, reaching a maximum at sea level, where the difference is measured by the mean head of the fresh water above the salt. Were it not recharged by rains, the fresh water would gradually flow down this gradient and over-run and mix with the salt water, while with the loss of the hydraulic head the salt water beneath the base of the lens would upwell and lift the remaining overlying fresh water into a position to be dissipated similarly, although at a decreasing rate.

The other element in the difference in head between the lens and sea level is caused by unbalanced pressures between the two bodies of water. Their effect may add to or subtract from that mentioned above. Unbalanced pressures result from short-lived causes; otherwise a new balance would be achieved. Unbalanced pressures may be caused by such factors as tidal fluctuations, heavy rains, or removal of ground water by pumping. Most underground water movement results from such causes.

In the pulsatory rise and fall of ground water as a result of tides, the change of level in a well may precede or follow the change in the water table of the adjacent area. Either the water table may rise first and water flow into the well, or the water in the well may rise first and serve to feed the adjacent ground-water body for a time, depending on the local hydrology. Changes in pressure may occur very quickly, theoretically with the velocity of sound in water. In a well in permeable material the starting of a pump a mile distant may be detected within a few seconds. However, the changes of level in the well and in the water table occur only as rapidly as the volume of water required by the difference in head can be gained or lost.

Where there is no well (Fig. 3A), the water will rise from an initial level d toward a level e which theoretically it can reach impelled by the hydro-

static pressure from a tidal rise in the sea with which there is interconnection. The height actually reached will depend upon the amount of water, considered as a proportion of the water-storage capacity of the aquifer between levels d and e, that can move through the underlying rock in the period of time available.

Where a well is present (Fig. 3B and C), a larger amount of water will be required than in A because of the volume of the well between levels d and e, but for wells having the same diameter the volume of water required to achieve a given rise in B and C is equal. Below the level d the total volume of openings is assumed to be equal in the three cases. The shallow well in B has few feeders; consequently, its level may lag below the level in the surrounding aquifer. Because of its greater depth the well in C intercepts more

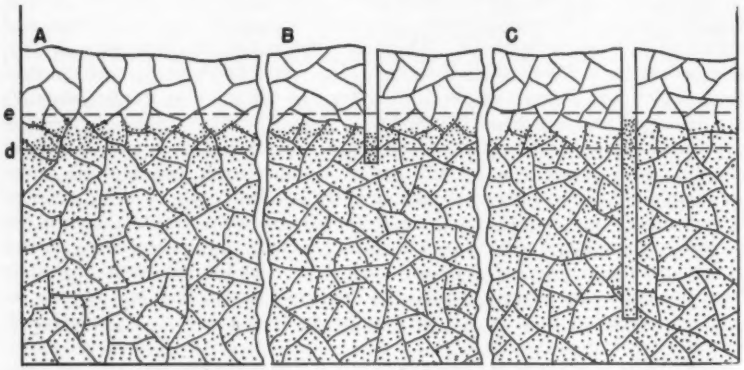

FIG. 3. Tidal rise of water table in a uniformly fissured aquifer. A, no well; B, with shallow well; C, with deep well. From initial level d, water rises toward level e, impelled by hydraulic pressure from the tidal rise of the sea nearby. In A, the rise takes place in fissures. In B, the level in the shallow well may lag behind the rise in the general water table because of the volume of the well to be filled. In C, the level in the well may rise more rapidly because the deep well is fed by more fissures.

feeders and it is likely that the greater ease of flow through the well column than through the ground around the well will result in the level in this well rising ahead of the level of the water table in the surrounding aquifer.

The extent to which a well encounters openings in the surrounding aquifer is a matter of chance. A random arrangement of large and small openings exists even in aquifers having relatively uniform permeability, and a well of given diameter and depth may intersect more or less than its share of the large openings. In wells of the same dimensions the chances are equal for encountering an excess or a deficiency of openings. Even though the widths of openings encountered in a given well may be evenly distributed above and below normal, the transmission capacities will be strongly skewed toward high values because the capacity of tubes, under laminar flow, increases as the

fourth power of the diameter, and of cracks as the third power of the width (1). Thus any single well-connected large opening, even if paired with an opening smaller than usual, will increase the transmission capacity above the average far more than the small opening will tend to reduce the average. Where a well or tunnel or sump intersects a random arrangement of openings of various sizes in an aquifer, it is statistically probable that the permeability will be augmented at a disproportionate rate as the porosity increases, very likely to an extent sufficient to surpass the volume requirement of a well at the water table. The larger the range in sizes of opening, the greater this effect is likely to be.

The water level in a well, therefore, may rise ahead of the water table in the surrounding aquifer, and it is more likely to do so the greater the depth of the well and the more variable the size of openings. By the same reasoning, the surface of a lake might rise more rapidly than the surrounding water table, but if the lake is shallow and has a large area its surface might rise more slowly. In any given case only direct observation is likely to show which will rise first, as usually not enough data on the openings are available to make a reliable prediction.

The tidal fluctuation in material having moderate and relatively uniform permeability results in an alternating thrust of salt water on fresh and fresh on salt, and owing to the alternate displacement of each by the other, the contact between the two is widened into a transition zone of mixed water through rinsing of each by the other (3) (Fig. 4A). Pressure changes caused by tides or addition of water from rainfall moves the zone of transition as a front toward the side of least pressure. In an aquifer not containing large fissures such widening of the zone of mixing is arrested after an equilibrium is reached as determined by the permeability and porosity of the material, the amplitude of movement, and the amount of outward movement of the rainfall increment. Such outward movement would be, in general, a small fraction of a foot for each rain, whereas movements resulting from the effects of tides are somewhat larger. The high-tide period is short, and its movement does not cause salt water to pervade far in fine-grained material. As long as the transition zone is essentially intact and moves back and forth as a unit during tidal and other movements, there will be no upsetting of the equilibrium or change of the mean position of the middle of the zone.

If the advance is not cancelled by effective reversal sea water will encroach upon the fresh-water lens, which becomes more saline and dense and assumes progressively lower positions. This decreases the hydraulic head, the system is no longer balanced, and salt water will move upward and displace fresh water until a new balance is reached. Lowering of the fresh-water table results in the loss of a much larger body of fresh water in the lower part of the lens.

In the case particularly of a relatively large pipelike fissure that leads fairly directly from the sea to the water table, the advance of salt water may not be cancelled by effective reversal. When sea level rises 1 or 2 feet above the position of balance with the water table, water may readily move through this conduit toward the water table at a rate much greater than the rate in the surrounding permeable material (Fig. 4B). This movement will tend

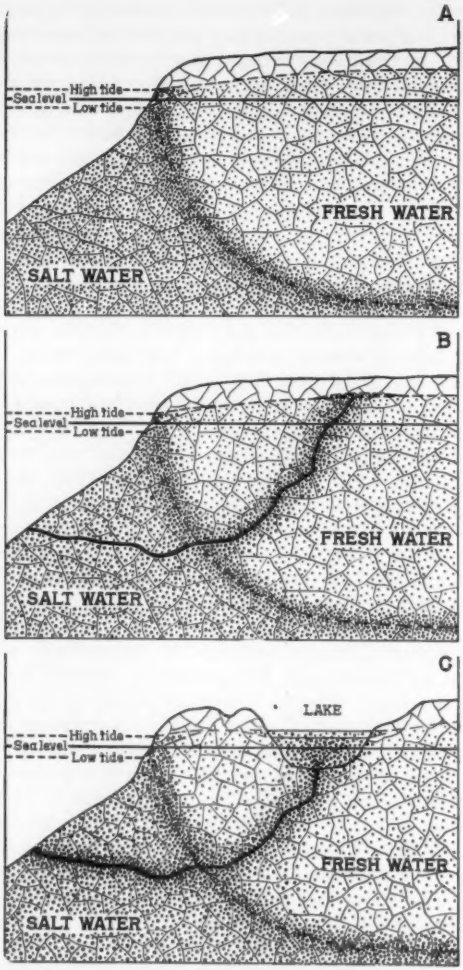

FIG. 4. Ghyben-Herzberg fresh-water lens in a low oceanic island.

A. An island composed of relatively uniform, moderately permeable material A transition zone exists at the interface of fresh and salt water. At high tide salt water may overrun the lens near the shore.

B. Effect of through fissure bringing salt water under tidal impulsion into fresh-water lens, initial stage. On a rising tide, salt water from the fissure rises faster and overtops the fresh-water table. The water in the fissure is less saline and dense than sea water, and hence it can rise above the sea's high tide. The saline water is not fully removed on the reverse tide, and the fresh-water lens is impaired. The fissure is actually surrounded by the lens, and does not divide it

to produce at the water table a low mound the apex of which is but little below the position of balance with high-tide level. The mound will tend to spread as water from the conduit enters the surrounding material. As the conduit thus acts as a feeder, more water moves through it than that merely necessary to fill the conduit between tide levels, and salt water penetrates a considerable distance. This condition will continue until the motion is reversed on the falling tide. Reversal of motion will not wholly remove the salt water; the greater the amount of movement and of mixing by the invading water on a forward movement, the less effectively will such water be removed by reverse movement. In the course of a few score tidal pulsations a large amount of salt water could be introduced into an originally fresh-water lens. Salt water also will penetrate the many small fissures that intercept the large fissure, and similarly not all will be removed when the tide reverses.

If openings of the type described are sufficiently numerous and large the salinity and density of the ground water will gradually increase and the water table of the area affected will be lowered. Such a process, carried far enough, could bring the general salinity of the water above the limit for domestic or agricultural use and might largely destroy the Ghyben-Herzberg lens. The appearance in wells of an increase in salinity with lowering of the water table has been the usual warning in Hawaii of widespread impairment of the lens. Relatively small islands composed of fissured or open-textured highly permeable material that permits substantial tidal fluctuations do not have an effective fresh-water lens.

Where the second case is modified to allow the large fissure to terminate in a depression, which because it extends below sea level contains a lake or pond, on a rising tide a much larger amount of water will move in from the sea (Fig. 4C). Unless the fissure is very long, or the tide is small, this motion will bring into the lake a substantial amount of salt water that has moved through the fissure in one or more cycles. With reversal, water will flow back out of the lake toward the sea through the subterranean opening, but only in part will it be the same water that flowed in.

If the inflow of salt water during a rising tide amounts to 1 foot in a lake having an average depth of 20 feet, after one inflow $\frac{1}{20}$ of the lake will consist of this water. Mixing is not complete, but in an open lake exposed to the wind considerable mixing occurs. Assuming complete mixing of salt water reaching the lake, if $\frac{19}{20}$ of the water remains at low tide, the proportion of fresh water after n pulsations would approximate $(\frac{19}{20})^n$; after only

as shown in the section. The saline water from the fissure does not settle by gravity and displace all fresh water below it, because the rainfall increment flows toward and escapes through the fissure as well as across the interface and at the shore.

C. Effect of through fissure bringing saline water into a depression with which it connects, initial stages. The capacity of the lake permits considerable tidal inflow of saline water, not all of which is removed on the reverse tide. The lake becomes saline, and the surrounding fresh-water lens is impaired more than in the previous case. The rainfall increment escapes through the lake and fissure as well as across the interface and at the shore. An equilibrium for these conditions is established in which the lens may be much smaller than in the initial stages shown here.

10 cycles the water in the lake would be approximately $\%_{10}$ fresh. Even if the fraction of sea water that reached the lake and mixed sufficiently to remain were much smaller, such as $1/_{100}$, the fresh water would be considerably reduced after a fairly small number of cycles ($0.99^{10} = 0.905$, but $0.99^{100} = 0.366$). Allowance must be made for the introduction of some rainwater, but the principle remains the same.

If the introduction of salt water is greater than the freshening effect from the rainfall increment, the lake will gradually become more saline; if less, the lake will freshen. Both effects occur, because rainfall is sporadic. If the tidal inflow is of fixed composition, say half sea water, and of sufficient amount, the lake will approach that composition during dry periods. Over a period of time sufficient to average the rainfall, the lake will achieve an equilibrium within a certain range. The lake will be part of a brackish lens that floats on sea water and has a mean level slightly above mean sea level. The level of the lake will be affected by the salinity of the water; higher salinity results in higher density of the water, and a lower surface level. The lake will have a tidal fluctuation that will follow that of the sea, but with a smaller amplitude.

In the first case (Fig. 4A), where the water table may rise and fall only slightly with diffuse motion in the uniform material, and with an amplitude that is a small fraction of the tide, a fresh-water lens may be maintained. In the second case (Fig. 4B) where a large fissure may bring salt water far into the fresh-water body and ultimately to the water table in small quantities, the intrusion of salt water may be great enough in the vicinity of the fissure to equal or exceed the additions from rainfall; this would impair but perhaps not destroy the Ghyben-Herzberg lens. In the third case (Fig. 4C), the intrusion of salt water may well be so great that the lake will become markedly saline. As the level of the lake is lowered, the water table in the vicinity will tend to be lowered. This will result in a much greater loss in the part of the lens below sea level, resulting in substantial impairment of the fresh-water lens. Whether the lake acts also as a feeder of saline water into its surrounding area depends upon whether the amount of inflow into the lake caused by a rising tide is sufficient to enable the level of the lake to overtop the level of the water table in the vicinity.

APPLICATION TO ANGAUR

Angaur provides a working model of the operations of a Ghyben-Herzberg fresh-water lens and illustrates the conditions postulated earlier for a low oceanic island. The data necessary for setting up a complete hydraulic inventory are not available for Angaur, but sufficient are known to permit useful conclusions. The estimated average addition each day to the head of ground water is about 0.1 foot. The average tidal range is about 4 feet. The plain in the southeastern part of the island (Fig. 2), resembles the case first postulated (Fig. 4A). The approximate elevation of the water table above mean sea level is about 2 feet, and the permeability of the rock is such that this head maintains a natural discharge sufficient to offset the rainfall increment. In

comparison, at Honolulu, where the distances concerned are much greater, more than 10 times this head is required to discharge the increment from a somewhat smaller rainfall. The fresh-water lens has two high and two low positions daily, with a range of about 0.5 foot. There are few or no through fissures, so the interface of fresh water and salt water moves to and fro with tidal fluctuations. Widening of the transition zone at the interface is limited by the rinsing action of the rain-water discharge. No through movement of salt water takes place, and the fresh-water lens endures and can be drawn upon for supplies of potable water in reasonable quantity.

Parts of areas in the northwestern part of Angaur that are distant from lakes, such as beneath the platform adjacent to the ring ridge (Fig. 2), probably correspond to the conditions postulated in the second case (Fig. 4B). Test borings in the northwestern part were sufficiently near saline lakes, however, that the salinity of the water encountered in the bore holes might be caused by the proximity of the lakes rather than by the effect only of a nearby subterranean fissure.

The areas containing the various lakes occupying mining excavations in the northwestern part of Angaur (Figs. 1, 2) exemplify the conditions postulated in the third case (Fig. 4C). The lakes exhibit various amounts of salinity. Their mean levels, which average less than 2 feet above mean sea level, in general inversely reflect the amount of salinity. Most levels are overtopped by high tides, and all are overtopped by the highest spring tides. The levels follow the fluctuation of the tides, but at reduced amplitude. The lakes that have the largest tidal fluctuation tend to be the most saline, a reflection of their interconnection with the sea through subterranean fissures. One lake (C) has negligible tidal fluctuation, and its water is the least saline of the lakes on Angaur. This lake also has the greatest depth, an apparent anomaly, but test drilling discloses that among the various lakes its bottom is still underlain by the greatest thickness of the fine-grained ore, which is much less pervious than fissured limestone.

Each lake has reached an equilibrium according to the principles discussed depending upon the size of the lake, the amount of tidal inflow, and the extent of fresh-water replenishment through rainfall. The equilibrium is not precise but has a range, for tides vary during the month and rainfall is sporadic and somewhat seasonal. Changes in the conditions upset the equilibrium and bring about trends that result in a new equilibrium fitting the changed conditions. Thus, further excavation may enlarge a lake and cause interception of additional channels, resulting eventually in a new equilibrium of tidal inflow and outflow, and a new range of tidal fluctuation, levels, and salinity. Contrariwise, other changes may improve conditions. The low salinity of Lake C would suggest that the salinity of other lakes might be decreased by covering their bottoms with material that has low permeability. Similarly, the difference in salinity between two parts of Lake B on opposite sides of a barrier used as a roadway across the lake, would indicate that in the case of other lakes the heavy inflow of salt water through particularly large fissures might be prevented from contaminating the entire body of water by erection of barriers to divide each lake into compartments.

REMEDIAL MEASURES

Remedial measures to retard or reverse the harmful trends were based upon the foregoing analysis. A program including extensive observations was recommended and established. Test holes were drilled in various critical areas, including areas of phosphate deposits (2, 3, 7, 9, 11, 15, and 16 in Fig. 1). At the lakes (Lakes A, B, C, D, and J in Fig. 1), several ponds, the established wells (Nos. 1–9 in Fig. 1), and the test holes, continuing observations were made on water levels; amplitude and lag of tidal fluctuations; and mineral content, pH, and temperature of the water. These observations enabled constant adjustment of the remedial measures to obtain maximum effectiveness as economically as possible.

The second part of the program began with partitioning of the lakes by barrier fills, starting with those of highest salinity. The elongate shape of many of the lakes on Angaur simplified partitioning. As there are no clay deposits on the island, coralline rubble, selected as fine-grained as possible, was used as fill material. The amount of saline admixture is thus reduced, as mixing is limited to those compartments that are in effective contact with fissures open to sea water.

Under the program, observations continue on each compartment, and those that fail to freshen are bottom filled to reduce tidal inflow. Where necessary, and in some places as part of a concurrent program to provide additional wetland agricultural areas, compartments are filled to slightly above sea level. Salinity changes are watched so that priority in remedial attention may be given to the more critical areas.

The stoppage of mining that was once imminent has been replaced by authorization for continuance of mining under the supervision afforded by the program. An operations plan is being pursued successfully whereby all deposits of commercial value approved for mining will be removed by the middle of 1955, resulting in a final total yield of approximately 3,500,000 tons of high-quality phosphate ore from Angaur.[2]

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[2] Based upon data furnished by the Phosphate Development Company, Tokyo.

LOWER PALEOZOIC MINERALIZATION NEAR BATHURST, NEW SOUTH WALES

R. L. STANTON

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ABSTRACT

The orebodies of the Bathurst area, in central western New South Wales, have developed in eugeosynclinal sediments of Lower Paleozoic age. When viewed regionally, mineralization shows no apparent structural affiliations, but it shows marked stratigraphical preferences in that every one of approximately forty orebodies occurs adjacent to one or other of two fragmental volcanic units. A refinement of this stratigraphical control is that orebodies occur in the shales adjacent to the volcanic rocks only in limestone-bearing localities. Metamorphism is related to ore deposition insofar as major orebodies occur only where the above stratigraphi-

cal requirements are satisfied, and the volcanic rocks have suffered silica metasomatism. Where the volcanics have been modified by this silicification, they show features similar to those of many igneous quartz porphyries.

The ore deposits are in the form of flat lenses conformable with the enclosing shales, and have the appearance of "replacement" rather than "vein" deposits. The ores themselves are copper-zinc and copper-zinc-lead sulphides with abundant iron sulphide. In many cases the last is by far the most abundant and the copper, zinc and lead sulphides occur merely as minor constituents of what is really a lens of pyrite or pyrrhotite-rich sediment.

A feature of the mineralization is that it has no apparent igneous source. The possibilities that the ores may have developed as a result of hydrothermal, "lateral-secretion" or syngenetic processes are tested on the available evidence, and the conclusion reached that none of these theories adequately accounts for all features. It is suggested that the copper, zinc and lead of the ores may have been derived, principally during metamorphism, from the volcanic rocks, and localized by syngenetic iron sulphide occurring in the adjacent shales. This iron sulphide is thought to have formed, by bacterial sulphate reduction, in areas of intense biological activity now marked by the occurrence of limestone.

It is suggested that the Bathurst orebodies may constitute a "type" and that orebodies developed in a similar way may be of fairly widespread occurrence. Such deposits should be localized in limestone-bearing facies of sedimentary sequences developed adjacent to island arcs and shelf areas. The general suggestion is made, too, that the interaction of migrating metallic ions—of hydrothermal or other derivation—with sulphur-bearing matter of sedimentary origin may be an important process of sulphide ore formation.

INTRODUCTION

The largest and best known of the Paleozoic sulphide orebodies of Eastern Australia are those of Mt. Lyell and Roseberry in Tasmania, Captain's Flat and Cobar in New South Wales, and Mount Morgan in Queensland, each of which has been the subject of numerous papers and company reports. In addition to these larger deposits there are, however, a great number of small orebodies of the same age which, as a result of their economic insignificance, have received almost no attention from geologists. It is among these that the Bathurst deposits fall.

The largest deposit of the Bathurst region was discovered near Burraga prior to 1877. This was worked as the Lloyd Copper Mine until 1919 and produced 18,600 tons of metallic copper together with some gold and silver. Most of the other mines produced no more than a few hundred tons of ore and most had been worked out by 1900.

During 1948 the present writer carried out a geological investigation of the Lloyd Copper Mine on behalf of Broken Hill South Ltd. While making an areal reconnaissance in connection with that work it was noticed that the mineralization of the whole district conformed to a pattern, and that, in their distribution and in their mineralogical features, the ore deposits bore some striking relationships with their geological setting. Some of these relationships—particularly those found to exist between the distribution of the orebodies and the occurrence of volcanic rocks and limestone—appear to be of fundamental importance. It has been found difficult to explain these, and

hence the origin of the orebodies, in terms of any one of the better known theories of ore genesis and it has been necessary to postulate a process incorporating features from several of these established conceptions.

It seems likely that similar relationships may hold in other mineralized districts but because they are not so well defined, or because the *regional* setting of the orebodies has not been considered, their significance has not been noticed. In suggesting such wider application of the writer's ideas, however, it is emphasized that there is no suggestion whatever that the postulated mechanism should be applied to all replacement deposits. The idea is put forward to explain the occurrence of certain lens-shaped base metal sulphide bodies, unrelated genetically to geological structure, conformable with the enclosing sediments and bearing the relationships with the distribution of limestone and volcanic rocks described in the present paper.

FIG. 1. Locality map. Area discussed shown shaded.

GEOLOGICAL SETTING

The area with which this paper is concerned lies just to the south of Bathurst (Fig. 1), one of the cities of central western New South Wales, and forms part of the Central Tableland region of the Eastern Highlands Belt. This part of the State is composed chiefly of Lower Paleozoic sediments that have been folded and intruded by granites and which, by Miocene time, had been reduced to a peneplain. During the late Tertiary Kosciusko epeirogeny this peneplain was uplifted and at the present time the region constitutes the dissected residue of this older landform. The Bathurst area itself is a little to the west of the divide between the eastward- and westward-flowing river systems of the State and is in the 2,500 to 4,000 feet altitude range.

As no detailed paleontological work has yet been done in the area immediately to the south of Bathurst, the exact ages of the sediments containing the

orebodies are not known. It is likely, however, that the lowest formations are not older than Upper Ordovician and that the highest are not younger than Upper Silurian.

Stratigraphy

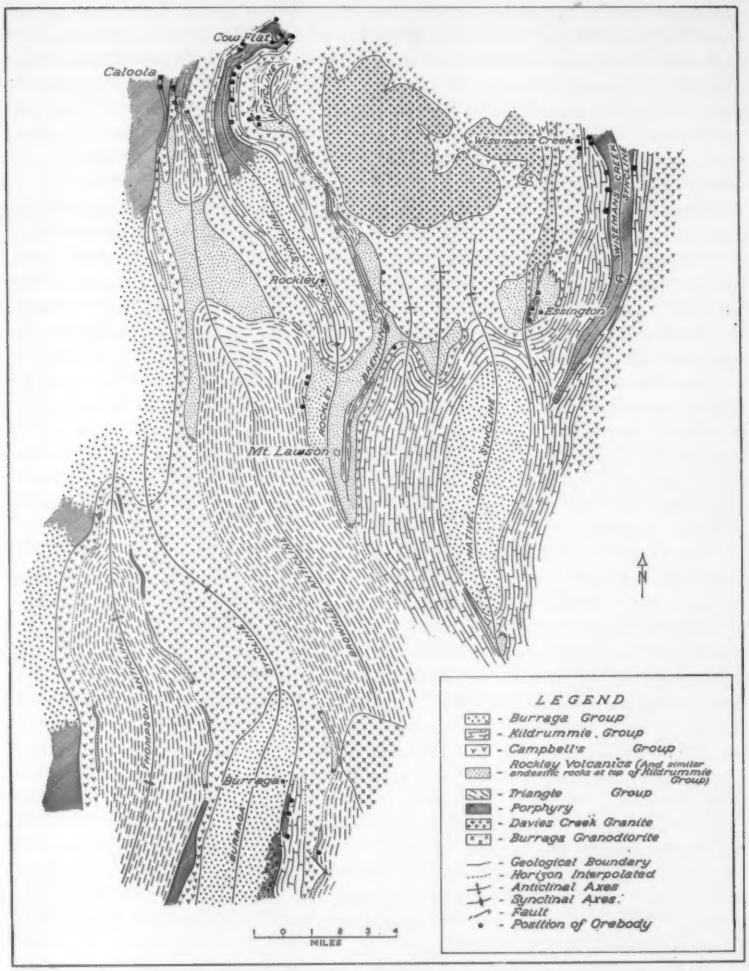
The total thickness of sediments exposed is rather more than 30,000 feet and all units are conformable with each other. Although shales and fine greywackes predominate, the sediments show considerable lithological variation indicating a broad division as follows:

Age	Name of unit	Approx. max. thickness
Lower Silurian?	Burraga Group	4,500′ plus
	Kildrummie Group	6,000′
	Campbell's Group	9,000′
Upper Ordovician?	Rockley Volcanics	5,000′
	Triangle Group	10,000′ plus

The *Triangle Group* underlies the other sediments over the entire area (Fig. 2), though as its base has not been found no estimates can be made of any variations in its thickness. It is composed of predominant shales, greywackes, isolated chert lenses, and minor tuffaceous bands. In some parts of the area, e.g., in the thin strip of Triangle rocks revealed in the core of the Brennan anticline just to the east of Mt. Lawson, the shales of the upper part of the unit contain a high proportion of carbonaceous material. These upper shaley members may also show a high iron sulphide content and in the locality cited abundant bedded pyrrhotite occurs. It seems likely that the development of this pyrrhotite commenced with the deposition of syngenetic iron sulphide which was then, during metamorphism, converted to pyrrhotite.

The thickness of the *Rockley Volcanics* ranges up to approximately 5,000 feet. The boundary between this formation and the Triangle Group is normally sharp though in some restricted localities the change is gradational over a range of up to 300 feet. The formation consists almost entirely of andesitic pyroclastics with subordinate andesitic and basaltic flows. The pyroclastic members are mostly fine but a few lenses of coarser material occur in which fragments, generally sub-angular, range to approximately one foot across. In a few places tuffs grade into small shale lenses but these are very minor. By far the major part of the unit is marine; trilobite remains have been found in the tuffs and fragments of bryozoa can often be detected in thin sections. Aqueous deposition is also indicated by the occasional gradation of pyroclastic into bedded shaly sediments, particularly at the base of the formation.

Transition from the Rockley Volcanics into the basal members of the *Campbell's Group* is normally sharp. Where the volcanics are absent, however, and the rocks of the Campbell's Group lie directly upon those of the Triangle Group, their base is difficult to define. Although their maximum thickness is great—approximately 9,000 feet—there is considerable variation in thickness and it is doubtful if this would average more than 2,000 feet. They comprise shales and sandy shales, tuffaceous shales, greywackes and conglomerates, and in many ways are very similar to the upper parts of the Triangle Group.


Cow Flat
Caloola
Wiseman's Creek
Wiseman's Creek
Rockley
Rockley
Basonyme
Rockley
Mt Lawson
Mt Lawson
Rockley
Rockley
Burraga
Burraga
Burraga
Rockley
Rockley
Rockley

developed over a large part of the area, the limestones of the group are of quite restricted occurrence. Allowing for folding, the area containing most limestone is a fairly well-defined strip running more or less southeast from Cow Flat, through Rockley to Campbell's River. Limestone occurs to the west of this, e.g., at Caloola, but less abundantly. To the east it thins out rapidly and is absent on the eastern limb of the Brennan anticline. It occurs again near Essington and Wiseman's Creek but less abundantly than in the Cow Flat-Campbell's River zone.

The major part of the Kildrummie Group is completely devoid of volcanic material. However, the change in sedimentation leading to the formation of the *Burraga Group* was accompanied, and in some cases slightly anticipated, by the deposition of andesitic tuffs similar in all respects to those of the Rockley Volcanics. The Group as a whole is composed principally of greywackes of dominantly volcanic derivation, with minor associated conglomerate, shale and the andesitic tuff.

Conditions and Tectonic Environment of Sedimentation.—The earliest detrital material—that of the Triangle Group—appears to have been derived principally from older metamorphosed sediments. The presence of carbon in some of the shales near the top of the unit indicates the presence of organisms (probably algal colonies) at that time. Syngenetic iron sulphide, commonly associated with the carbonaceous rocks, has probably resulted from bacterial sulphate reduction.

The crystalline character of the Rockley Volcanics points to a terrestrial origin but whether they were sub-aerial or redistributed cannot be determined owing to the obliteration of primary features by metamorphism. The presence of large, angular, crystalline volcanic fragments suggests that the present area was not far removed from the source of these and this is supported by the rapid thickening and thinning of the formation as a whole. Conditions of sedimentation during the formation of the Campbell's Group seem to have been rather similar to those prevailing during the formation of much of the upper part of the Triangle Group. The sediments here, however, average a little coarser, contain more volcanic material and are rather richer in carbonate. The complete absence of volcanic fragments from the limestone and their associated marls and shales indicates volcanic quiescence and the existence of stable conditions during the period of their formation. However, a pronounced change in sedimentation was ushered in by a resumption of vulcanism and the development of the extensive and very uniform feldspathic greywackes of the Burraga Group. These, and the associated shales, were derived largely from a volcanic terrain.

As the sequence of sediments is both very thick and of great areal extent, a geosynclinal formation seems obvious. Initial rapid deposition of the lithologically similar Triangle sediments must have occurred in a sinking trough; there is a marked increase in the ratio of greywacke to shale as the top of the unit is approached and this is accompanied by increased development of bedding—a feature suggested by Pettijohn to be typical of a geosynclinal sequence. The presence of the volcanic units indicates a eugeosynclinal environment.

The marked change of facies, from greywackes and shales to limestones

and shales, and the cessation of vulcanism, after the Campbell's sediments suggests the onset here of a period of stability characterized by the intensification of biological activity and the development of coralline limestones in the shallower parts of the trough. Although some of the limestone appears to be biostromal, the large lenticular masses are almost certainly true bioherms. It is probable that the spatial relationship between the distribution of the Rockley Volcanics and that of abundant limestone is due to the fact that both have been deposited in shallow water adjacent to a structural high such as those occurring along the inner andesitic arcs of present day island festoons in the southwest Pacific and in the East and West Indies.

The minor vulcanism that commenced near the end of the Kildrummie sedimentation was probably the first manifestation of the renewed instability that was to cause the development of the Burraga rocks. A general instability of the trough apparently persisted throughout the formation of the feldspar-rich greywackes, shales and tuffs of this group.

Geological Structure

The major fold structures of the area conform with the regional trend in this part of eastern New South Wales, and can be ascribed to the late Silurian east-west compression that affected the whole of the Tasman Geosyncline during the Bowning orogeny. The intensity of folding varies from fold to fold, and in some cases from one part to another of an individual structure. Some folds, or parts of these, are fairly open, but in other cases folding is tight, and has resulted in parallelism of fold limbs and some overturning.

A feature of the area is its general lack of faulting. Much small scale faulting (i.e., of the order of inches) has been observed, but the area is almost completely devoid of major faults. Only three of size sufficient to show on the map have been found, and these are very minor features.

Metamorphism

Regional.—Folding has been accompanied by low grade regional metamorphism of the sediments which, as a result, now occur principally as phyllites and low grade schists. The pelitic rocks contain most commonly the assemblage chlorite-muscovite-quartz-epidote-albite. Variation of this assemblage is brought about by the appearance of biotite, much of which is a green variety (pleochroic from pale brown to dirty olive green). Where metamorphism is clearly of biotite grade the latter is typically honey brown to very deep brown. Metamorphism has caused little more than a variable recrystallization of the limestones and dolomitic rocks and the development of the assemblage calcite-chlorite-quartz in the calcareous shales. In the greywackes of the Burraga Group the response of the matrices has been essentially similar to that of the normal pelitic rocks and the abundant feldspar has suffered varying degrees of saussuritization. The andesitic rocks, particularly the tuffs, have been converted to typical greenschist. Feldspars have been saussuritized in precisely the same way as in the greywackes and the pyroxene has been mostly replaced

by uralite and chlorite. Metamorphism of the fine groundmass of these rocks has developed abundant chlorite, epidote and fibrous actinolite with minor amounts of carbonate, quartz, albite and biotite.

If the pelitic rocks are taken as "indicators" it is clear that the Bathurst rocks fall within the greenschist facies. Although both muscovite-chlorite and biotite-chlorite subfacies occur, boundaries between areas of the two metamorphic grades have not been mapped.

Metasomatic.—A feature of the area is the occurrence of rocks having the appearance of regionally metamorphosed quartz and quartz-feldspar porphyries. In Australian geological literature rocks in many respects similar to these have frequently been referred to as "sheared porphyries." They occur in a number of localities in the Lower Paleozoic terrain of the Eastern Highlands and show a high degree of conformity with the sediments in which they occur, and a limited variation in petrology. In many cases they appear to be fragmental. In different localities various workers have considered them to be igneous (in the form of sills or porphyritic flows) or "intrusive tuffs."

Initially the present writer worked on the assumption of an igneous origin for the occurrences at Bathurst, but after a closer investigation it became clear that the problem was not nearly so simple. The petrological problem involved has, in fact, been found to be a major one in itself and hence outside the scope of the present contribution. However, as the origin of these rocks is important from the point of view of ore genesis it is necessary to consider them briefly.

In the Bathurst area the "porphyritic" rocks occur principally within, or as a stratigraphical equivalent of, the Rockley Volcanics and the Burraga Group; very minor occurrences are found in the Triangle and Kildrummie Groups. The evidence of outcrop pattern, schistosity and jointing indicates conclusively that whatever their origin, they were in their present position relative to the associated sediments prior to the final folding movements. Where sedimentary structures occur in the stratigraphically equivalent volcanic rocks, i.e., in the Burraga Group, corresponding relict structures are conspicuous in the porphyritic rocks. Relict bedding, with stretched pebbles, is common in all occurrences of porphyritic rocks on this horizon.

Under the microscope they consist of larger quartz and feldspar grains set in a schistose groundmass. This is composed of quartz-chlorite-muscovite-(feldspar-epidote) or quartz-chlorite-biotite-(feldspar-epidote) assemblages depending on the prevailing grade of metamorphism. Quartz is generally, though not invariably, the dominant mineral of the groundmass and occurs as fine, crenulate interlocking grains. Muscovite and chlorite blades and shreds are included in most of the fine quartzes. Biotite occurs in flakes up to 0.5 mm in length and tends to occur in the shadow of the larger quartz and feldspar particles. In the porphyritic rocks corresponding to the Rockley Volcanics the "phenocrysts" are almost exclusively quartz, which is a light but obvious blue in hand specimen. It is generally eye-shaped though commonly of bi-pyramid form. Such quartzes vary in size up to about 1.5 cm across and average about 1.5 mm. Feldspar phenocrysts are dominant in the porphyries of the Burraga Group horizon, a feature consistent with the corresponding greywackes. The subordinate quartz phenocrysts are essentially similar to those of the lower porphyries.

On the basis of the criteria of Grout (23) and from the similarity of these rocks to those of the Porcupine area as described by Holmes (26) and Evans (17), it is concluded that they have developed during, and, to a lesser extent, following regional folding, and that they have assumed many of their present features as a result of silica metasomatism. It seems likely that high permeability, coupled with the comparative instability of the volcanic assemblages under conditions of low-grade metamorphism, caused selective silification of the volcanic units. The principal result of silification was the development of a ground mass of fine interlocking quartz that replaced both fine and coarse constituents of the parent volcanics. The quartz "phenocrysts," in reality porphyroblasts, have developed by the coalescing of small quartz grains of the groundmass, and by outgrowth. In the former case, as envisaged by Goodspeed (21) at Cornucopia, coarser mosaics developed first and, with some crystallographic reorientation, the formation of single crystal porphyroblasts followed. In many cases these were further enlarged by outgrowth. Apart from some minor modification and outgrowth, the feldspar "phenocrysts" are detrital.

This breakdown and replacement of the volcanic rocks has been accompanied by the emigration of much of their original content of iron, magnesium and calcium and also of the minor elements such as copper, lead and zinc which were formerly camouflaged within mineral lattices. It is here that porphyry formation becomes important in ore genesis.

Igneous Rocks

Apart from isolated residuals of Tertiary basalt flows, two groups of igneous rocks occur in the area. These are the Davies Creek granite, emplaced prior to the final folding movements and now appearing in the northern part of the area, and the Burraga granodiorite, a post-folding intrusive outcropping on the southeastern edge of the map.

The Davies Creek intrusive outcrops are three separated masses. The two more westerly of these are remnants of a sill, and the eastern, north-south trending mass is a dike. The relationships between the topographic contours and the outcrop patterns of the first two masses indicates that these are at least largely conformable with the enclosing sediments, and that their bases are at comparatively shallow depth. The granite itself shows pronounced foliation and this, together with the general pattern of jointing, is in conformity with that of the enclosing sediments, indicating intrusion either before or during folding.

The Burraga intrusion—a massive granodiorite—transgresses the strike of the enclosing sediments and has given rise to numerous unstressed dikes. These features, together with its complete lack of foliation, clearly indicate the intrusion's post-folding age.

THE OREBODIES

Distribution

The two most striking and significant features of the pattern of mineralization are the occurrence of the orebodies only in areas of volcanic rocks and of limestone.

All orebodies of the district are associated with either the Rockley Volcanics or the Burraga Group; it is a feature of the whole area that there is not one instance of ore having been found other than adjacent to one or other of these two volcanic units or the porphyritic rocks derived from them. With only isolated exceptions, however, the orebodies do not occur within the volcanic rocks but in the adjacent shales; where ore does occur in volcanic material this always carries a high proportion of shaly matter. The shales containing ore are fine grained and commonly contain carbonaceous material.

The first and most striking feature of the distribution of mineralization, therefore, is the exclusive association of the orebodies with the two volcanic formations and the occurrence of ore as two "horizons."

The second feature of the relationship between stratigraphy and ore occurrence is the preference of the latter for limestone-bearing localities. As orebodies are in places hundreds of feet, or as at Burraga even greater distances, from actual limestone outcrops this relationship becomes apparent only when a regional view is taken. The proximity of ore and limestone is, however, a persistent feature of the mineralization. In view of this relationship it is a little surprising to note that sulphide has never been found within limestone; there is no suggestion whatever that the ores have formed as limestone replacements.

An obvious negative feature of the distribution of ore is its apparent lack of any relationship with broad geological structure. It appears that:

(i) there has been no tendency for ore deposition to occur in the crests or troughs of folds,

(ii) orebodies do not necessarily accompany stretched fold limbs,

(iii) where folds are asymmetrical there is no preference shown for either shallow or steeply dipping limbs,

(iv) ore deposition shows no relationship to variations in direction or intensity of fold axis plunge,

(v) although the Lloyd Copper Mine orebody is known to have been affected by post-lode faulting there is no evidence that it, or any other orebody of the district, has been localized by faulting or shearing. Where faulting is known to have occurred there is no evidence of mineralization.

Ore occurrence shows quite a definite relationship with metamorphism on the upper horizon where, provided the stratigraphical conditions have been satisfied, mineralization has occurred principally where the rocks of the Burraga Group have suffered silification such that they have assumed a porphyritic appearance. This does not appear to be a necessary requirement for mineralization on the lower horizon. In both cases almost all orebodies occur in rocks of biotite grade.

Mode of Occurrence

All the orebodies appear to have been in the form of flat, rather irregular, lenses. The width of these rarely exceeded six feet though it has been reported by Carne (11) that the Lloyd Copper Mine orebody was as much as forty feet thick in parts. Although this was worked down the underlay for

about 2,000 feet, the depth of the others rarely exceeded 200 to 300 feet and most of them were smaller than this.

All the major deposits occur on the upper horizon; those on the lower horizon were, from the mining point of view insignificant, and it is doubtful whether production from these would have exceeded 1 percent of that from the upper horizon orebodies of Burraga, Wiseman's Creek and Cow Flat.

None of the orebodies had well defined "walls," concentrations of sulphide simply graded out into barren rock on either side. In some of the orebodies a minor amount of sulphide occurred in quartz veinlets, but this type of ore was subordinate to that occurring as "impregnations" of shale. In the Burraga, Essington, Cow Flat and Rockley areas, deposition of sulphides has been partly guided by small-scale metamorphic structures such as flow and fracture cleavage. These structures have obliterated any bedding that might have occurred in the shales, and the sulphides themselves certainly show no sign of preserving the outlines of earlier sedimentary structures. At Wiseman's Creek, on the other hand, much of the ore shows poorly defined macroscopic banding more or less parallel to the schistosity and the original bedding of the enclosing shales.

Chemical and Mineralogical Features of the Ores

All the ores of the district contain copper and zinc, and some of them contain lead, the ratios of the three metals varying considerably from one orebody to another. In the copper-zinc ores ratios vary from Cu/Zn = 40/1 to Cu/Zn = 1/9. For orebodies in which Cu/Zn ratios are high, copper-zinc plots are fairly linear, but such linearity clearly decreases with a decrease in the value of the ratios. In the zinc-rich ores the copper-zinc plots are quite irregular. A notable feature of the mineralization is that lead occurs only in the upper horizon orebodies, in which it is in places an important constituent. Lead has never been detected in material from the lower horizon. For these ores, lead and zinc plots are fairly linear for low Pb/Zn ratios, but there is a clear decrease in this linearity with an increase in the value of the ratios. Lead and copper show no regular relationship.

Variations in the proportions of copper, zinc and lead for the district as a whole are shown in Figure 3.

The zinc-rich ores seem to be confined to a small area round Wiseman's Creek, in the northwestern corner of the area. In their mode of occurrence and in their microscopical features they are very similar to those of Captain's Flat (13, 16) and Roseberry, Tasmania (41). The principal sulphides are pyrite, sphalerite, chalcopyrite, and, on the upper horizon, galena. Minor constituents are tetrahedrite and arsenopyrite. Pyrite, and the very occasional arsenopyrite, are always subidiomorphic to idiomorphic in form. Pyrite cubes occur in clusters and poorly defined bands set in a mesostasis of sphalerite, chalcopyrite, tetrahedrite and, where present, galena, and are commonly corroded by the latter minerals—particularly sphalerite. The rare arsenopyrite rhombs show similar corrosion. Pyrite is prominent in ore of all grades, and is almost the only sulphide present in the poorer material into which the

copper-zinc-lead mineralization grades. The sphalerite, chalcopyrite, galena and tetrahedrite occur simply as aggregates of allotriomorphic grains. Boundaries are "mutual" and there is some tendency for the grains to interlock. As has been noted by Stillwell and Edwards in the Roseberry and Captain's Flat ores, these three sulphides show limited segregation into ill-defined, discontinuous bands which are usually of the order of 2 to 3 mm wide. Veining among these sulphides is negligible.

In the other ores of the area chalcopyrite is generally by far the dominant sulphide, the subordinate sphalerite and galena almost invariably being in-

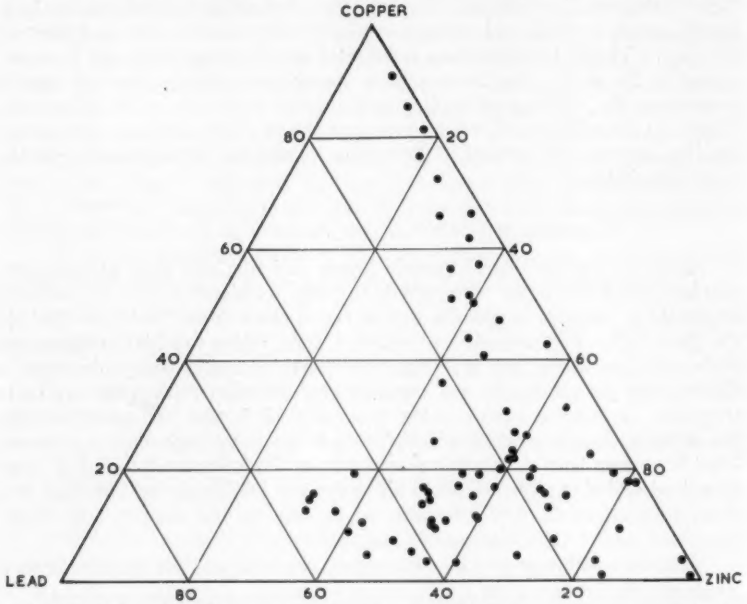


FIG. 3. Triangular diagram showing the proportions of copper, zinc and lead in representative Bathurst ores.

cluded by ore or in contact with the larger areas of chalcopyrite. Although much of the iron sulphide is present as either primary or secondary pyrite, pyrrhotite is an important constituent, and in some of the copper orebodies is present almost to the complete exclusion of pyrite. Marcasite is common and, with most of the secondary pyrite, has resulted from the decomposition of the pyrrhotite. Minor ore minerals found in the copper orebodies of the upper horizon are dyscrasite, native bismuth, bismuthinite, arsenopyrite and native gold, all of which occur within larger areas of chalcopyrite or, less commonly, within pyrrhotite.

Most of the copper-rich ores show evidence of exsolution. "Asterisks" of sphalerite in chalcopyrite are common, and show definite preferred orientation within any one host grain, indicating control by the crystal structure of the chalcopyrite. Spongy and dendritic sphalerite, within chalcopyrite, also appears to have developed by exsolution. Chalcopyrite within sphalerite occurs as emulsion blebs, commonly in seriate arrangement, and as segregation

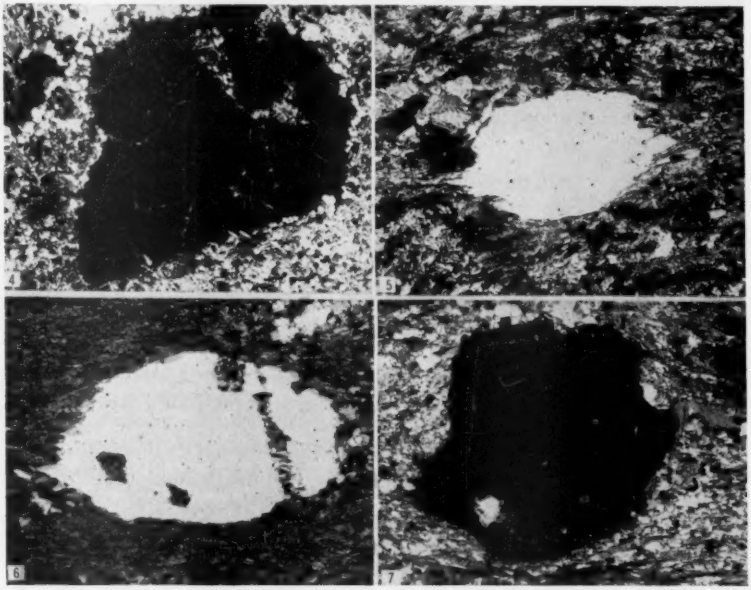


FIG. 4. Quartz porphyroblast in one of the Bathurst "porphyries" showing webs of sericite inclusions. The latter possibly indicate former outlines of small quartz grains which have grown together with the assumption of a uniform crystallographic orientation. ×-nicols, × 30.

FIG. 5. Typical quartz "eye" with projecting thin tongues along foliation of groundmass; the quartz shows no sign of strain. ×-nicols, × 35.

FIG. 6. Porphyroblast similar to that of Fig. 5, enclosing schistose material whose foliation is parallel to that of the groundmass. ×-nicols, × 30.

FIG. 7. Outgrowth of quartz on subidiomorphic quartz "seed" outlined by fine sericite. A tendency to "eye form" and absence of strain are obvious. ×-nicols, × 20.

veinlets. A very minor quantity of pyrrhotite within chalcopyrite occurs as crudely oriented rods and blebs, suggesting the possibility of minor exsolution of pyrrhotite from chalcopyrite.

No exsolution textures have been preserved in the zinc-rich ores, though it is recognized that this may indicate complete exsolution of all constituents, rather than a lack of former exsolution relationships.

Paragenesis of the Major Sulphides.—The evidence of textures strongly suggests that, in all the ores, primary pyrite was the first of the sulphides to form. The pyrrhotite of the copper ores formed later than pyrite, but largely preceded chalcopyrite. As some of the pyrrhotite appears to have exsolved from chalcopyrite, some overlap in the deposition of this pair is indicated. It is possible, however, that this pyrrhotite may have resulted from high temperature replacement of earlier pyrrhotite by chalcopyrite, and subsequent regurgitation with temperature fall.

Textural features give little or no indication of the paragenesis of chalcopyrite, sphalerite and galena, though the chemical features of the ores do suggest a sequence. If all the orebodies of the area are considered together, it is seen that the five principal sulphides occur only in the groupings

Iron sulphide (pyrite or pyrrhotite)
Iron sulphide-chalcopyrite
Iron sulphide-chalcopyrite-sphalerite
Iron sulphide-chalcopyrite-sphalerite-galena

and hence all ores of the area fall into one or other of the metal groupings—iron; iron-copper; iron-copper-zinc; iron-copper-zinc-lead. There are no other groupings such as iron-lead or lead-copper. This seems to suggest either:

(i) that during mineralization of the area, there were present ore solutions of four, and only four, compositions, each capable of producing ores of one or other of the metal groupings given, or

(ii) that the metals have been added to the ores, from essentially similar solutions, in a strict order—iron, copper, zinc and finally lead—and that ores lacking any of these metals have not been completely developed. The latter might, for instance, have been due to the cutting off of "mineralizing solutions" prior to the completion of sulphide deposition in any given orebody.

The writer favors the second alternative, and hence considers that, although there may have been some overlapping between successive pairs, chalcopyrite, sphalerite and galena have been deposited in that order.

Conditions of Formation.—(i) Temperature. The significance of the presence of pyrrhotite in ores seems to be a matter of rather widely divergent opinion, and has been discussed by Schwartz (36, 37), Spence (39), Blanchard (5), Garretty (20) and others. It appears that geological "evidence" as to the temperature of formation of pyrrhotite is largely interpretation, and is of very doubtful reliability. The laboratory evidence of Allen, Crenshaw and Johnson (1) seems more dependable, and strongly supports the view that pyrrhotite is a high temperature mineral. At the pressures prevailing during ore deposition, its temperature of formation is probably in the vicinity of 600° C. In the ores where primary pyrite and pyrrhotite occur together, the latter is clearly the younger, at least some of it having formed at the expense of the pyrite. This indicates that at least during the early part of their formation, these ores were at a temperature probably approximating to 600° C. In the

ores where there is no evidence of pyrrhotite having formed at the expense of pyrite, or that the present pyrite has resulted from the breakdown of pyrrhotite, it seems that such high temperatures were never attained.

The mineral pairs involved in the exsolution textures of the ores are:

Chalcopyrite-sphalerite
Sphalerite-chalcopyrite
Chalcopyrite-pyrrhotite

As unmixing of sphalerite from chalcopyrite is known to occur at about 550° C (10), the preservation of this texture indicates that most of the ores involved were, at some stage of their history, at temperatures above 550° C. Unmixing of the other pairs is, of course, known to take place at lower temperatures. There is also the suggestion that the cooling of the orebodies in this temperature region was fairly rapid.

(ii) Stress. The relationships between the opaque and non-opaque minerals of the ores seem to suggest that these may have suffered regional metamorphism together with the rocks that enclose them. One of the more obvious features of the ores is the lack of clear evidence of replacement of the metamorphic silicates of the host rocks by the sulphides. Apart from one doubtful case—the presence of three small particles of tremolite, with the same extinction positions, in a sulphide grain from one of the Cow Flat orebodies—no groups of similarly oriented residuals of silicate or carbonate have been found in sulphides. Silicates commonly include idiomorphic pyrite and other sulphides, indicating, in part at least, development in their present form after the deposition of the sulphides. Sulphides certainly form tongues between silicate grains, but the reverse is also the case. In some cases sulphide has developed in cracks in silicates, but there is little or no evidence of actual replacement. In general, sulphide and silicate, and carbonate where present, occur simply as equigranular aggregates, sulphide and silicate being of essentially the same form and size. (The banding of the sulphides noted in the zinc-rich ores is very similar to that developed in the metamorphic silicates of the host rocks, but there is no convincing evidence that this results from the preservation of silicate structure by the replacing sulphides.) These features suggest the simultaneous development of the two groups of minerals—at least in their present form.

The lack of evidence indicating formation of the sulphides later than the metamorphic silicates is common to all orebodies and suggests that, whatever their original mode of emplacement, all of them have been recrystallized. The only factor capable of causing recrystallization of more or less similar degree over a wide area is regional metamorphism, and it seems most likely that the present silicate assemblages, and silicate and sulphide textures, have developed together during folding. The widespread similarity of metamorphic assemblages and structures indicates that all parts of the area have much the same tectonic history, and the deformation textures of the sulphides—particularly the orientation of the sphalerite twinning—conform with this in suggesting that all of the orebodies have suffered essentially the same degree of metamorphism.

ORE GENESIS

Application of the Hydrothermal Theory

It is clear that the orebodies show many of the features of hydrothermal replacement, both in their field occurrence and their mineralogy. There are, however, some features that do not appear to be compatible with such an origin:

(1) In many cases ore has been formed exactly on the contact of the relevant volcanic formation and shale, the width of ore being taken up in the shale. This suggests that ore may have been localized by the impounding action of the overlying volcanics. However, in other instances, the ore occurs at more than 100 feet below the volcanic horizon concerned, and has, therefore, apparently been deposited before the ore-bearing solutions ever encountered it.

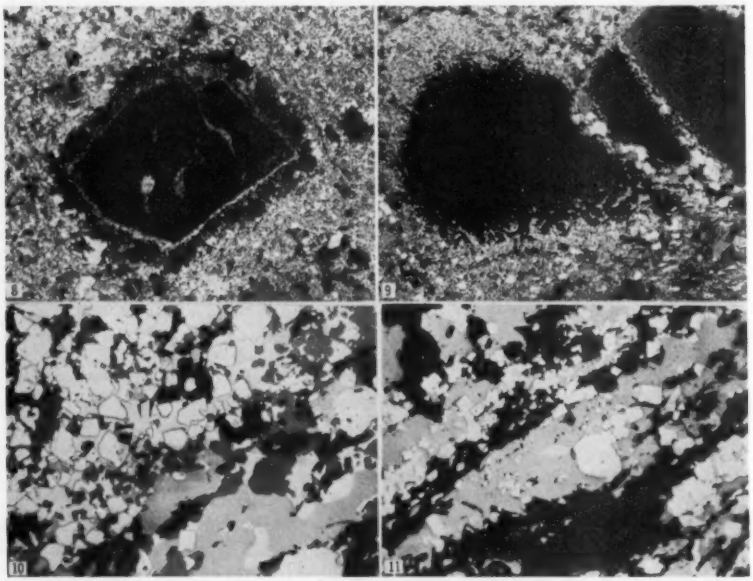


FIG. 8. Quartz porphyroblast with compact nucleus and spongy outgrowth. Schistose material is again included. ×-nicols, × 25.

FIG. 9. Quartz grain showing frayed or spongy margin; groundmass included. This suggests development by outgrowth and incorporation of fine quartz particles of groundmass. ×-nicols, × 25.

FIG. 10. Copper-zinc-lead ore from Wiseman's Creek. White, some relief, pyrite; off-white, galena; light gray, tetrahedrite; dark gray, sphalerite; black, gangue. Upper left half shows part of a pyrite-rich band. × 40.

FIG. 11. Typical poorly defined banding of the Wiseman's Creek ores; rich in tetrahedrite, with associated pyrite and galena. × 40.

This suggests that in some cases ore deposition is due neither to the direct physical guidance nor to the chemical action of the volcanic rocks.

(2) Had the ore-bearing hydrothermal solutions, in their upward migration, been guided by the undersurfaces of the volcanic beds, it would have been expected that they would have tended to have moved up the pitch of the fold structures. However, orebodies show no tendency to occur beneath the volcanics at the crests of anticlines.

(3) Some orebodies of the lower horizon occur immediately above the Rockley Volcanics. Clearly these could not have formed as a result of impounding by the latter, although it is possible that the sharp physical-chemical break in going from volcanic to sediment may have caused some precipitation.

(4) Assuming the ores to have had a common origin in one magma, it is most likely that the same solutions provided ore for both horizons. On such an assumption it seems strange that whereas almost all orebodies of one horizon contains lead—and in places an abundance of it—those of the other contain none. As it is the upper horizon that contains lead, it might be suggested that there is here a clear case of zoning. Galena, an "intermediate" temperature mineral, has not been deposited until the upper and cooler locus has been reached. There is little in this argument, however, as the mineralogical evidence suggests that some of the lower horizon orebodies may have been formed at slightly lower temperatures than those of Cow Flat, some of which contain appreciable lead.

(5) Probably the most significant evidence against the existence of rising solutions is provided by stratigraphy. It has already been noted that ore deposition has always occurred in limestone localities, and that where no limestone occurs—even though all other factors are favorable—no ore has formed. Further points are:

(a) Although below the limestone, the lower orebodies show as distinct a preference for limestone-bearing areas such as those of the upper horizon. Therefore, if the ore deposited from rising solutions, these apparently sought out the limestone areas, although in doing this they shed some of their load before the limestone was reached. It seems remarkable that ore deposition should have been influenced by rocks the ore solutions never reached—and even failed to reach by some hundreds of stratigraphical feet.

(b) The upper orebodies, at the top of the Kildrummie Group, are always above the massive limestone. In places, as at Cow Flat, massive limestone may occur within a few feet of ore, though commonly, as at Wiseman's Creek, it is some hundreds of feet away from the actual site of ore deposition. No sulphides occur *in* limestone, however; not one instance of replacement of limestone by sulphide has been found. Limestone has, therefore, not been *directly* responsible for precipitation, if it were responsible at all.

(c) If the ore did arrive by rising solutions, there is now the problem that some hundreds of thousands of tons of sulphides must have moved through or past masses of limestone of great purity without one speck of sulphide being precipitated. The preference of sulphides for limestone is well known, and it is difficult to believe that these could ever have encountered such limestone

masses without at least some precipitation. It thus seems very probable that the sulphides never moved past the limestone at all.

(6) The orebodies show no clear relationship with igneous intrusives. Those at Essington are certainly close to the granitic dike that runs through this area, though as the stratigraphical associations here are precisely similar to those of other orebodies with no adjacent granite, and as orebodies occur nowhere else along this dike, it seems almost certain that this proximity of ore and intrusive is fortuitous. It is recognized that a deeper igneous mass—

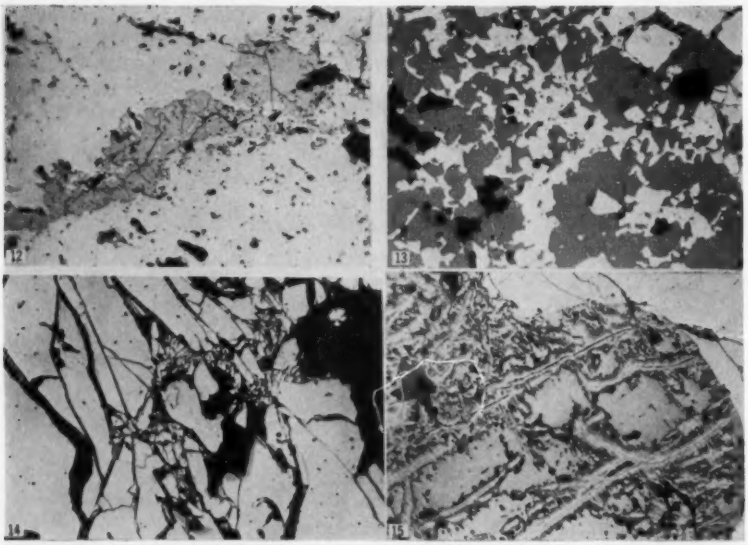


FIG. 12. Irregular band of pyrrhotite in chalcopyrite from Burraga; between ×-nicols the pyrrhotite is finely granular and the chalcopyrite shows deformation twinning. × 40.

FIG. 13. Chalcopyrite-sphalerite band in zinc-rich ore, with pyrite band in top right. When etched the sphalerite shows secondary twinning; traces of such twin lamellae show some preferred orientation, suggesting deposition or recrystallization during folding. × 40.

FIG. 14. Pyrite showing cataclasis. × 25.

FIG. 15. Alteration of pyrrhotite to marcasite. Former inclusions of sphalerite in pyrrhotite, are now isolated in marcasite. Light is chalcopyrite. × 40.

the possible parent of the granitic dike and sill—may have been the source of ore solutions but, although the possibility that an as yet unrevealed source rock does occur must be acknowledged, its apparent lack is a weak point in the application of the igneous hydrothermal theory in this particular district.

(7) Although the sulphides may have been deposited initially as replacements of the shale country rock, the almost complete lack of evidence for the

replacement of silicates by sulphides immediately throws doubt on the replacement origin of the ores *as they now occur*. However, if the ores have suffered metamorphic recrystallization this certainly does not rule out the possibility that they had earlier formed by a normal process of hydrothermal replacement.

Application of the Lateral Secretion Theory

There seem to be two principal requirements for the application of this idea at Bathurst:

(i) The rocks to which the orebodies are characteristically adjacent should, where unaccompanied by actual concentrations of the metals, contain traces of the latter.

TABLE I

SEMI-QUANTITATIVE SPECTROGRAPHIC DETERMINATION OF COPPER, ZINC AND LEAD IN VOLCANIC AND "PORPHYRITIC" ROCKS OF THE BATHURST DISTRICT

Sample number	Rock type	Cu	Zn	Pb
1	andresitic tuff	T	FT	VVFT
2	andesitic tuff	ST	FT	VVFT
3	andesitic tuff	ST	FT	VVFT
4	andesitic tuff	ST-L	FT-T	VVFT
5	andesitic tuff	T	T-ST	VVFT
6	andesitic tuff	T-ST	FT	VVFT
7	greywacke of Burraga Group	VFT	FT	FT
8	greywacke of Burraga Group	FT	FT-T	VFT
9	greywacke of Burraga Group	FT	FT	FT
10	porphyritic rocks derived from	VFT	FT	VVFT
11	andesitic tuffs	VFT	VFT	VVFT
12		VFT	N	VVFT
13		VFT	N	VVFT
14	porphyritic rocks derived from	VFT	?	VVFT
15	Burraga greywacke	VFT	?	VVFT
16		VFT	N	VVFT

Key: L—Low percentage; 0.1%–3%.
ST—Strong Trace; 0.03%–3%.
T—Trace; 0.01%–0.1%.
FT—Faint trace; less than 0.03%.
VFT & VVFT—minute amounts, just detectable.
N—Nil.

Analyst—N. Whittem, Defense Standards Laboratory.

(ii) Where they are accompanied by orebodies, the metal content of such rocks should be lower than in (i).

The rocks to which the orebodies are characteristically adjacent—the Rockley Volcanics and the Burraga Group—certainly contain detectable quantities of the relevant metals (Table 1). This aspect is discussed more fully later, but there is no doubt that this first requirement is satisfied. Where the larger orebodies of the area—those of the upper horizon—occur, and hence where the volcanic rocks of the Burraga Group have suffered intense silicification,

there has been a sharp drop in the metal content of the latter. This is shown by spectrographic analysis (Table 1). For these orebodies, therefore, the second condition is also fulfilled. Where the orebodies are very small, as on the lower horizon, it is extremely doubtful whether a detectable drop in the metal content of the adjacent volcanics could be expected.

For the upper horizon at least, this occurrence of heavy metals in the volcanic rocks, where no ore bodies appear, and the absence of such metals from them where their boundaries have been loci for ore deposition, is a pronounced relationship. Thus, the possibility that some process such as lateral secretion may have contributed to the development of the deposits cannot be dismissed. However:

(1) Such a mechanism does not explain the relationship between the distribution of limestone and the distribution of ore.

(2) Had lateral secretion of sulphides taken place over distances greater than the order of 100 feet (the distance of some of the orebodies from the adjacent volcanic rock) it is surprising—as was noted in discussing the hydrothermal theory—that none of the limestone has been replaced by sulphides.

(3) Lateral secretion provides no mechanism for the localization of the sulphides.

Application of the Theory of Syngenetic Deposition

As almost all sulphide of the Bathurst district occurs as disseminated grains in low-grade metamorphic products of shales, and as, in bulk, vein formation has been more or less negligible, it might be suggested that deposition has been a part of sedimentation. Syngenetic concentration of the metallic sulphides would presumably result from:

(i) the development of a reducing environment during sedimentation,

(ii) subsequent activity of anaerobic sulphur-producing bacteria,

(iii) "fixing" and concentration of the traces of iron, copper, zinc and lead, normally present in sea water and marine organisms, as sulphides,

(iv) incorporation and preservation of these sulphides in oxygen-poor bottom muds.

It has already been noted that much of the shale in which the orebodies occur contains carbon, and that in some localities this is abundant. This certainly indicates that abundant organic matter was present during the deposition of the shales, and suggests that in the bottom waters, or at least only at a very short distance below the mud-water inter-phase, anaerobic conditions prevailed. Both a suitable environment and an energy source were therefore available for sulphur-producing bacteria, and there is little doubt that they would have existed at the time. (It is recognized that in orebodies in other parts of the world the coincidence of carbon and ore has been otherwise explained. However, there is nothing in the microscopical evidence here to suggest precipitation of the ore minerals by the carbon itself.)

A syngenetic origin would neatly account for the marked stratigraphical preferences of the orebodies, and, as is discussed more fully later, is capable of explaining the relationship between the occurrence of limestone and distri-

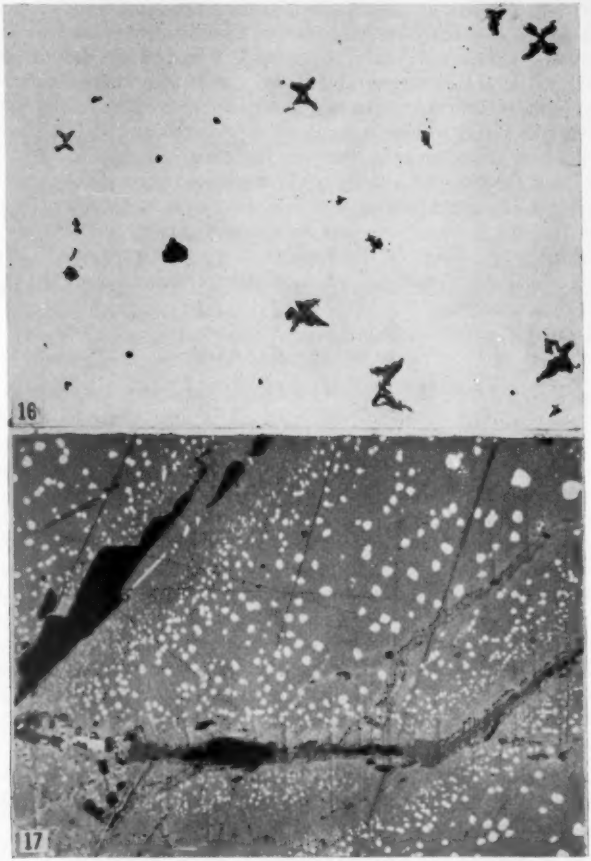


FIG. 16. Sphalerite "asterisks" in groundmass of chalcopyrite showing a preferred orientation controlled by the crystal structure of the chalcopyrite. × 75.
FIG. 17. Emulsion texture of chalcopyrite in sphalerite from Rockley. × 100.

bution of ore. Further, such might explain very conveniently the existence of this relationship and, at the same time, the complete absence of replacement of limestone by sulphides. As with the other ideas, however, there are some features that are difficult to account for.

(1) Were the orebodies syngenetic, and hence had they been formed even before the rocks of the Burraga Group had been deposited, it is difficult to see why their occurrence should apparently be linked with the metamorphism of the latter.

(2) If the sulphur of the deposits has been produced by bacteria, and the metals from sea water and decaying marine organisms, it is far from clear why the lower horizon ores should all be devoid of lead, while most of the upper ores carry it—in some cases in abundance. It is also difficult to account for variation in the metal ratios. In fact, as the amounts of the heavy metals present in sea water and marine organisms are so constant, it is difficult to see why, if the ores are syngenetic, they are not chemically almost identical.

(3) Even allowing for differences in the chemical constitution of the ores, the occurrence of certain groups of metals—i.e., iron, iron-copper, iron-copper-zinc and iron-copper-zinc-lead—and the complete absence of any other grouping, is difficult to explain on the basis of a syngenetic origin. There seems no reason why there should not be combinations such as iron-lead or copper-lead, but these never occur.

Alternative Hypothesis

As each of the foregoing theories accounts quite well for some of the features of the Bathurst orebodies, but as each is inadequate to explain other features, it appears that the present case is not a clear-cut one at all, and that at various stages of mineralization, each process may have contributed. It is now suggested that the orebodies were formed by metasomatic replacement of syngenetic iron sulphide. The process visualized is simply that of "favorable bed replacement," and differs from current ideas only in that the favorable horizon is thought to have been sulphide, rather than silicate or carbonate. It is further suggested that the source of the introduced copper, zinc and lead has been the volcanic rocks to which the orebodies are invariably adjacent. Migration of the metals from the volcanic source rocks may have taken place by diffusion, in an aqueous medium, commencing during diagenesis and accelerating—and reaching a climax—during regional metamorphism. The validity of this idea seems to rest on four main points:

(i) That, in the light of present knowledge of modern marine sulphide formation, iron sulphide could have formed in the Bathurst sediments as syngenetic deposits having (allowing for minor metamorphic modification) the form and the distribution of the present orebodies.

(ii) That copper, zinc and lead formerly occurred in the volcanic rocks, and, further, that they occurred in sufficient quantity to supply the tonnages of metal now known to occur in the deposits.

(iii) That during diagenesis and regional metamorphism these metals were capable of migrating from the volcanic rocks and of moving short distances into the adjacent sediments, so encountering any iron sulphide-rich lenses that happened to be close to the boundary of the two.

(iv) That, having encountered the iron sulphide, the metals were capable of replacing some of the iron, so depositing as sulphides themselves.

These points are now considered.

The Formation of Syngenetic Iron Sulphide.—In much of the geological literature bearing on the formation of syngenetic iron sulphide it seems to be

implied that this is almost completely confined to deep, stagnant bodies of water, which are characterized by restricted circulation and local oxygen impoverishment. Here the sea water itself carries little or no oxygen, and the whole environment is anaerobic. Rankama and Sahama (32) make the following points:

(1) Sapropelic muds rich in organic remains are deposited in stagnant waters.

(2) Stagnant conditions exist in closed basins that have shallow outlets to the sea and in which lack of circulation causes the loss of oxygen.

(3) Under such conditions, the sulphates are partly reduced to sulphides, probably largely by the action of bacteria. In like manner, hydrogen sulphide is formed in stagnant waters from the vegetable sulphur-bearing compounds in the reduction processes caused by the bacteria.

(4) The presence of hydrogen sulphide causes the precipitation of sulphides of iron and copper in the bottom sediments.

(5) The conditions and processes outlined above occur in some Norwegian fjords, in the Black Sea, in numerous tropical lagoons, and in some salt lakes.

In the Bathurst sediments, one of the features of sulphide occurrence is that it is close to limestone, which is largely coralline. It is well known that for coral growth the sea water must be well oxygenated, and that its depth above the growing colonies is limited; such conditions are, clearly, the direct antithesis of those normally considered to be required for the formation of sedimentary iron sulphide, and, apart from lagoon deposition, it does not appear that formation of limestone and iron sulphide could take place in a common sedimentary environment. This latter point, however, is not supported by marine biological research in modern sediments.

Although comparatively little seems to be known of the mechanism of formation of FeS_2 in marine muds, it has been suggested that combination of iron compounds with H_2S or sulphur first produces hydrotroilite ($FeS_x \cdot nH_2O$ or $FeS \cdot nH_2O$), which is converted by addition of sulphur to "melnikovite" and finally to pyrite or marcasite depending on the pH of the environment. The distinguished marine biologist, Dr. L. G. M. Baas Becking, has recently carried out an investigation into this problem, and concludes (personal communication) that the conversion of the marine iron hydroxides to FeS_2 is probably along the following pattern:

Assuming the formation of H_2S by bacterial reduction, this encounters, in solid phase, ferrous and/or ferric hydroxides—

$$H_2S + Fe(OH)_2 \rightarrow FeS + 2H_2O$$
$$3H_2S + 2Fe(OH)_3 \rightarrow 2FeS + S + 3H_2O$$

Thus, the primary product of the interactions of H_2S and iron hydroxide is troilite, and both FeS and S will be present at the mud-water inter-phase. FeS_2 is then formed by

$$FeS + S \rightarrow FeS_2$$
$$2FeS + 2H_2S + O_2 \rightarrow 2FeS_2 + 2H_2O$$

the latter reaction tending to deplete the oxygen content of the environment. The FeS_2 may develop as pyrite or marcasite according to the value of the prevailing pH (15).

As the S and H_2S required for the formation of troilite and pyrite is produced by sulphate reducing bacteria, the ecology of these organisms is of fundamental importance in determining the environment of formation of sedimentary iron sulphide deposits. Galliher (19) lists five important groups of marine micro-organisms contributing to the sulphate-sulphide-sulphate cycle. Of these, his fifth group—those heterotrophic bacteria capable of reducing sulphates and other oxygen-rich sulphur compounds of the sea water to H_2S—are the most important in iron sulphide deposition. These obtain their energy from carbonaceous matter on the sea floor and, therefore, as sea water offers an almost unlimited supply of sulphate, it is on the distribution of this carbonaceous matter that the occurrence of the organisms depends. Thus, in turn, the formation and distribution of troilite in the marine muds depends on the distribution of decaying organic material. The correlation of the organic content of black muds and their ferrous sulphide has, in fact, been shown by Galliher in samples collected from Monterey Bay, California—an open marine basin characterized by fairly rapid sedimentation and strong and variable water currents. It is therefore of interest to consider the general distribution of decaying organic matter at the sea bottom.

ZoBell (43) states: "The largest bacterial populations generally occur in water near shore where there is much terrigenous pollution." Galliher states of the Monterey Bay deposits: "It is clear that there is a decrease in carbon and sulphide contents of the muds with increase in depth of sample although the relation is only approximate. However, this general conclusion is justified by contrasting the intense black muds of the shallow regions of the bay (0 to 40 meters) with the blue-gray muds of the greater depths (700 to 800 meters)."

Galliher points out that the major amount of organic detritus is assimilated by micro-organisms—either floating or living in the sediments—before it is transported far from the land or settles to any great depth, and he puts forward the generalization that organic carbon in the muds, and consequently iron sulphide, decreases with increase in depth of water. (This idea has been emphasized to the present writer by Dr. Baas Becking, in personal discussion.)

As these near-shore deposits are continually washed by well oxygenated sea water, it possibly seems inconsistent, in view of our knowledge of the importance of stagnant basins, to suggest that such shallow water environments could be highly conducive to the formation of sulphide. However, it appears that, within only a few centimeters of the mud-water inter-phase reducing conditions develop in the mud. ZoBell states:

> Whenever profile series have been examined, a progressive decrease in the bacterial population of bottom deposits from the surface downwards has been observed. At the mud-water inter-phase aerobes predominate. . . . With increasing depth of mud, bacteria capable of growing aerobically decrease in abundance more rapidly than those which grow in the absence of free oxygen, and at depths exceeding 10

to 20 cm., anaerobes generally predominate. A decrease in the sulphate content of mud with increasing core depth is indicative of the activity of the sulphate reducers in situ.

From this biological evidence, it appears that there are two important marine sedimentary environments in which decaying organic matter is abundant, and hence where sulphide forms and accumulates:

(i) In stagnant, poorly ventilated water. The supply of organic matter here may not be great, but what *does* settle is effectively conserved by the anaerobic "cover." This appears to be the ideal environment for the deposition of iron sulphide, and is the one generally recognized by geological workers.

(ii) In a zone close to shorelines, where organic matter is supplied in such abundance that some inevitably is incorporated in the mud, escaping oxidation and providing a source of carbon and hydrogen for sulphate-reducing bacteria.

In normal, open sea environments almost no organic matter accumulates, and hence there is little or no sulphide formation.

Baas Becking, who has observed the activities of sulphate-reducing bacteria and the formation of iron sulphide in sediments in many parts of the world, has pointed out to the writer that concentrations of organic matter, and hence of the dependent bacteria, have a "patchy" development on the sea floor. Sulphide-rich sediment therefore normally begins to form as patches, rather than as a continuous sheet, and on developing into three dimensional bodies, these patches become lenses, distributed through the main body of sediment in which they form. Although troilite, the form in which the sulphide is initially deposited, may be oxidized by other bacteria to the sulphate, this cannot occur once stable pyrite (assuming an alkaline pH) has been produced. Sulphur and iron in the combination FeS_2 are thus removed from the cycle, and in this way may accumulate to form high concentrations.

Sulphide in the Bathurst Sediments.—The recent marine biological studies concerning the occurrence of organic matter and sulphides in near-shoreline zones are not entirely applicable in the present case. The Bathurst sediments are Lower Paleozoic—of Upper Silurian age and older. As, during this period, land plants were poorly developed or absent, it is almost certain that the supply of terrigenous organic matter to the near-shore muds would have been negligible. However, coral reefs have always been the center of intense biological activity—not only of the coral building organisms, but also of the large associated assemblages of algae and other marine life. There seems little doubt that some of these organisms, on dying, would have been incorporated in the associated fine muds, protected from oxidation, and finally digested by anaerobic sulphate-reducing bacteria. Baas Becking has, in fact, noted the accumulation of appreciable quantities of sulphide on the seaward slope of coral reefs in the East Indies. It appears that, owing to the high oxygen content of the surrounding water, little decaying organic matter is found at a great distance from the reef areas, and hence sulphide formation is confined to sea-floor localities fairly close to them.

The iron sulphide lenses and iron sulphide-bearing orebodies (many of which are almost entirely pyrite or pyrrhotite carrying, comparatively speak-

ing, only very minor quantities of other sulphides) of the Bathurst area have an association very similar to that which one would expect had they been known to have formed as marine deposits. Although *never in* limestone, they invariably occur close to it. Further, they occur in sediments that contain carbonaceous matter. Some of the sulphide, as has been pointed out in the section on stratigraphy, occurs stratigraphically below the limestone, but even in these cases, it is still close to the latter. Such localities would very probably have been the scene of intense biological activity even prior to the actual growth of coral.

Copper, Zinc and Lead in the Volcanic Rocks.—Vulcanological investigations have shown quite definitely that salts of the heavy metals are often important constituents of the sublimates deposited round volcanoes and fumaroles. The greatest number of observations have, of course, been made round the classical Mediterranean areas, but significant work has also been done by Allen, Zeis and Fenner in the Valley of Ten Thousand Smokes. As has been noted by Fenner (18), the importance of the heavy metals in volcanic gases is probably even greater than is indicated by their occurrence as sublimates since, when in their most common combination—the chlorides—they are relatively highly volatile and at high temperatures are largely dissipated in the air and, as these compounds are so highly soluble, they are readily washed away by rain. In reference to Vesuvius, Fenner states:

> Lacroix gives an account of the fumarolic products after the 1906 eruption. Compounds of lead and copper were found under various conditions: copper compounds are more plainly recognizable unless present as the white sub-chloride, $CuCl_2$. This is believed to be the form in which it is volatilized, but it has not been found deposited. All the chlorides are easily washed away by rain. After the 1906 eruption, he found, moreover, that by treating with boiling water scoriae in which megascopic examination did not reveal any salts, much chloride of lead, of potassium and of sodium was extracted. Some crystallized galena was found, and its deposition was attributed to reaction between the vapors of $PbCl_2$ and H_2S.

Fouque and Lasaulx, in their studies at Etna in 1880, have stated that in the 1865 eruption, great quantities of NaCl, HCl, NH_4Cl, and $FeCl_3$ were given off. Small amounts of copper chloride and copper oxychloride gave a green color to the fumarolic deposits, and there were also detected traces of chlorides and oxides of manganese, cobalt and lead. Although the two metals occur at both localities, it has been suggested that copper is the characteristic metal of the Etna fumaroles, anl lead those of Vesuvius.

The observations of Allen and Zeis and Fenner (18) on the occurrence of the ore elements in fumaroles of the Valley of Ten Thousand Smokes are also of interest. In 1919 Zeis reported the presence of heavy metals in many fumarolic deposits there, lead, zinc and tin being the most common. Interaction of large quantities of associated acid gases and other volatile compounds, such as those of the heavy metals, with extruded pumice, produced notable mineralization of the pumice. A fluorine content of pumice as high as 3.8 percent was found. Zeis also noted deposits of magnetite which he estimated to be of the order of several thousand pounds. An analysis of such magnetite revealed the presence of notable traces of the heavy metals.

In considering the fragmental volcanic rocks of Bathurst, it is interesting to note Fenner's statement on the work of Zeis: "The work . . . on the incrustations collected in 1919 has shown that minute amounts of a great variety of metals were widespread, and that the total quantity was large, but most of them were dispersed in the porous tuff."

Owing to difficulties of analysis, there appear to have been few determinations made of the traces of heavy metals in older volcanic rocks. However, in their paper on the metallic constituents of some American igneous rocks, Sandell and Goldich (33) give copper, zinc and lead analyses of lavas ranging from olivine basalts to rhyolitic obsidians. All three metals were found to be invariably present, generally as substantial traces (Table 8). From their analyses of volcanic and other igneous rocks, Sandell and Goldich came to the following (among other) conclusions:

(a) The distribution of copper, zinc nickel and cobalt in the Kearsage and Greenstone flows of Michigan can be correlated with the distribution of the major chemical constituents. Nickel and cobalt show a close relationship to MgO and CaO, whereas copper and zinc appear to be related to the distribution of iron.

(b) Zinc shows a strong affinity for iron and enters minerals such as magnetite-ilmenite, pyroxenes, amphiboles and biotites. Additional factors, little known, appear to influence its distribution.

(c) Copper, like zinc, is influenced by the distribution of iron, although, in contrast to zinc which is commonly abundant in granitic rocks, copper shows a preference for the subsilicic ones.

(d) Lead in igneous rocks shows a close relationship to potash, although all the lead is not present in potassium minerals.

Table I shows, in a semi-quantitative way, the metal content of the rocks of the two volcanic units at Bathurst. A high copper content is clearly a feature of the andesitic rocks. Zinc is always detectable, but is distinctly subordinate to copper. Lead is only just detectable. In the samples of the highly feldspathic greywackes of the Burraga Group, copper is distinctly lower than in those from the andesites. Zinc is possibly rather higher than copper, while lead, though low, is distinctly higher than in the other volcanic unit.

Examination of polished sections of both rock types has not shown the presence of sulphides, apart from a minute amount of pyrite, and hence it seems most likely that at least a large part of the heavy metals they now contain occurs as substitutions in the relevant mineral lattices. In view of this, the occurrence of the metals in the two rock types are in substantial agreement with the findings of Sandell and Goldich, and fit in quite well with their mineralogy and their potassium, calcium, magnesium and iron contents.

Although the percentages of copper, zinc and lead occurring in these rocks are very small, it is clear that, when large quantities of rocks are considered, their total tonnages are considerable. This does not include possible films of sublimate that might easily have occurred in the formerly porous tuffs, as noted by Fenner in Alaska, and which might very easily have found their way from the volcanics into adjacent sediments during diagenesis.

Migration of the Metals.—It seems certain that the metallic sublimates associated with the volcanic fragments would dissolve and migrate readily. Where such fragments fell into the sea, any coatings of these compounds would be immediately dissolved—only the material trapped in fine fractures and cleavages, and in the cavities of vesicular materials, would be retained and incorporated in the rocks as they settled on the sea floor. As sedimentation proceeded, and the volcanic fragments became compacted, any metallic halides released from cracks and vesicles would dissolve in the intergranular water trapped in the sediments. Normal diffusion of the soluble salts from a region of high concentration to one of relatively low concentration—i.e., from the volcanic rocks into the adjoining detrital sediments—would then be expected to take place.

Heavy metal ions occurring within silicate lattices would probably not migrate—at least to any great extent—unless the rocks containing them suffered fairly severe modification. This is indicated by the persistence of such metals in the volcanic rocks at Bathurst, which have suffered regional metamorphism to biotite grade. On the other hand, where metamorphism has produced changes in rock composition, as distinct from non-compositional changes in texture and mineralogy, it seems likely that movement of the heavy metals might have resulted. Such metamorphism has, in fact, occurred where the andesites and the greywackes have been modified to form "porphyries." The spectrographic work certainly suggests that the mineralogical changes involved in porphyry formation have been accompanied by a flight of iron, magnesium and calcium, and that these in turn have been accompanied by copper, zinc and lead. In every case, there has been a sharp drop in copper, zinc and lead in going from the unsilicified rock to the corresponding "porphyritic" type. There is no reason for believing that the volcanic rocks, where they have suffered intense silicification, initially contained less of these metals than where they were not silicified. Therefore, there is a strong indication that this metamorphism has been accompanied by a migration of copper, zinc and lead from the affected parent rock.

It thus appears that, during diagenesis and metamorphism, the small amounts of the heavy metals occurring in the volcanic rocks as soluble salts and as constituents of minerals would have been capable of leaving their parent rocks and of migrating into adjacent sediments in which, by comparison, their concentrations were initially low. Such movement would have represented a simple tendency towards geochemical equilibrium. However, even assuming the presence of an aqueous medium for migration of the metallic ions, it is thought doubtful that these would have moved outside a range of a few hundred feet on either side of the source beds. Therefore, although iron sulphide lenses are distributed throughout much of the adjacent sediment, only those close to the volcanic rocks would have been encountered by the migrating copper, zinc and lead.

Replacement of the Iron Sulphide.—In view of the unknown, but probably complex and variable chemistry of the environment in which replacement took place, it is—as with the application of most theories of ore genesis—more or less impossible to give a precise explanation for the substitution of the iron

by the incoming copper, zinc and lead. On the other hand, polished section data, and that of synthetic replacement experiments show quite definitely that ions of these metals can substitute in the iron sulphide minerals. There are many descriptions of ores in which pyrite or pyrrhotite have been replaced by chalcopyrite, sphalerite and/or galena; further, Schouten's experiments (35) have shown that a number of these replacements take place readily under laboratory conditions.

Suggested Mechanism of Formation of the Bathurst Orebodies

It is now suggested that ore localization commenced with the syngenetic development of lenses rich in iron sulphide. These, although stratigraphically above and below the limestone, formed in limestone-bearing areas as a result of the factors discussed. The spatial relationship between limestone and ore occurrence was thus the result of sedimentary factors, not of any effect the limestone may have had on later hydrothermal solutions.

Normal marine sedimentation was interrupted twice by the deposition of fragmental volcanic beds. Both of these, as indicated by spectrographic analysis, contained traces of the heavy metals, such as copper, lead, and zinc. These probably occurred as soluble salts (sublimed chlorides for the most part) deposited within vesicles and minute cracks and cleavages, and as camouflaged ions in the lattices of some of the rock forming silicates. The lower volcanic horizon—the andesitic rocks of the Rockley Volcanics—consisting almost entirely of ferromagnesian minerals, contained a comparatively high proportion of copper, with lesser amounts of zinc. The upper volcanic horizon—the highly feldspathic greywackes and subordinate andesites of the Burraga Group —on the other hand, carrying a high proportion of feldspar and only subordinate ferromagnesian material, contained small quantities of lead, as well as copper and zinc.

Following their incorporation in the geosynclinal pile, the volcanic rocks represented bands comparatively rich in the heavy metals, "sandwiched" between layers of normal detrital sediments comparatively poor in them. Assuming the retention of some intergranular water within the sediments, and the presence of at least minor quantities of soluble sublimate compounds, these, by normal chemical diffusion, would have commenced to migrate from the metal-rich volcanics to the metal-poor sediments during compaction and diagenesis. With the onset of regional metamorphism, and the replacement, in some areas, of the metal-bearing minerals of the volcanics by silica, the migration of copper, zinc and lead would have been greatly accelerated. With heavy silicification it is possible that, locally, geochemical equilibrium might have been approached, and the volcanic rocks almost completely deprived of their earlier metal content.

No reason for the paragenesis of chalcopyrite, sphalerite and galena can be suggested. The ionic radii of copper, zinc and lead do increase in that order, suggesting possible differences in the rates of diffusion of the ions of each metal, although the difference between those of copper and zinc seems negligible. Further, in an aqueous environment the ions would be solvated, in which case their radii are all almost identical.

During diagenesis and metamorphism the fine microcrystalline pyrite of the iron sulphide-rich lenses would have started to recrystallize. This would have commenced with the development of small cubes scattered throughout the fine sulphide, and presumably would have ended with the development of masses of more or less idiomorphic pyrite such as occurs in the Wiseman's Creek ores, and in the lenses of pyrite found elsewhere in the area. With increase in temperature accompanying regional folding, the iron sulphide in some areas was converted to pyrrhotite.

In their outward diffusion from the volcanic rocks, it would have been inevitable that the copper, zinc, and lead ions should encounter any iron sulphide-rich lenses in the immediately adjacent sediment. According to the timing of diffusion and the metamorphic conditions under which this took place, they might have combined with sulphur provided by microcrystalline pyrite, recrystallized pyrite, pyrrhotite or with that resulting from the pyrite:pyrrhotite conversion. Gradual elimination of the iron would have taken place through chalcopyrite, iron-bearing sphalerite to galena, the completeness of the paragenesis (i.e., the ratio of zinc to copper and the incidence of lead) depending on the nature of the source rocks and the intensity and duration of metamorphism. This precipitation of the metals as the insoluble sulphides would have led to a local drop in their concentration in the intergranular solution, with consequent further diffusion towards the iron sulphide-rich lens concerned. In this way considerable concentration of the metals might have been achieved, and lenses of sediment containing notable quantities of the metallic sulphides, and showing the form and constitution of the orebodies now found, developed.

Later, with the fall in temperature following folding, any pyrrhotite present would have become metastable, and would have begun to dissociate to form secondary pyrite and marcasite.

CONCLUSIONS

The suggestion that orebodies of a certain type may be genetically linked with nearby deposits of limestone and volcanic rocks points to the possibility of some interesting relationships between ore occurrence and regional tectonics.

In many cases—and certainly in the Lower Paleozoic of New South Wales —limestones and fragmental volcanics are themselves genetically linked in that both have been deposited adjacent to structural highs such as those of present-day island festoons. Both rock types are, in fact, characteristically deposited in the sequences adjacent to the inner (volcanic) arcs of the East Indies and the south-west Pacific. The islands of these festoons are almost invariably ringed by fringing reefs, on the seaward side of which organic debris and hence iron sulphide accumulate. Periodically normal sedimentation is interrupted by a volcanic phase, to give precisely the geological features found in the Lower Paleozoic rocks near Bathurst and elsewhere in Eastern Australia.

Such a relationship between ore deposition and island arc formation suggests the following:

(1) That this type of orebody should develop along a zone, corresponding to the line of the parent arc, up to many hundreds of miles in length. Such orebodies should not, however, be confused with true magmatic deposits, which

might, as the result of folding and intrusion of the major geosyncline, follow a rather similar pattern.

(2) As limestone and volcanic material is normally distributed in a discontinuous way along the length of island arcs, the occurrence of the associated mineralization would be expected to be similarly discontinuous. Where conditions have been ideal for the formation of large lenses of iron sulphide-rich sediment, and where such areas have also been the site of heavy deposition of volcanic material, major orebodies would be expected to result. This coincidence of particularly large sulphide-bearing lenses with particularly heavy pyroclastic accumulation would, however, be expected only in a minority of cases, and the incidence of larger orebodies would accordingly be sporadic. The more general development of smaller iron sulphide lenses, on the other hand, would have led to the development of numerous minor orebodies. These would now be expected to occur almost anywhere where limestone and volcanic material have been deposited and later folded together, as at Bathurst.

(3) In their form and associations the orebodies would exhibit a number of characteristic features:

(a) They would be flatly lens-shaped, or would occur as extensive disseminations in the enclosing sediments.

(b) They would be conformable with the enclosing sediments.

(c) Although possibly involved in fold structures, they would not be genetically related to these, except insofar as plastic deformation led to thickening of the sulphide lenses in axial regions of folds.

(d) Although the parent sulphide lenses might have sharply defined boundaries as the result of sudden changes in conditions of sedimentation, many of them would be expected to have ill-defined margins, at least in part. This, and possible incomplete displacement of iron by the later metals, would lead to the development of "assay boundaries."

(e) Such orebodies would tend to grade out into barren pyrite, where displacement of the iron had been incomplete. Further, it might be expected that barren, or near-barren, pyrite or pyrrhotite bodies would occur elsewhere in the same, or a similar, stratigraphical unit.

(f) In any one district, the orebodies of this type would occur only in one, or in a limited number of, stratigraphical units, all of which would show evidence of organic activity in their carbonate and, possibly, carbon, content. Such units would be "favorable beds," but not in the sense implied when referring to hydrothermal replacement.

(4) The folding of the sulphide-bearing sediments of the orogenic belts, and their subsequent uplift and erosion, would yield "metallogenetic regions" of varying, but generally great, extent. Ore-bearing districts, within the boundaries of such broad regions, would occur in areas of that particular facies of sedimentation described.

(5) Although it is conceded that very small quantities of copper and zinc, derived from organisms such as molluscs, might be deposited with the iron sulphide during sedimentation, it seems most likely that syngenetic deposition of these elements would be more or less negligible. It seems logical to suggest that the elemental constitution of the final orebodies would depend on the mineralogical constitution, and hence trace element content, of the associated

igneous fragments. Thus, on the basis of the work of Sandell and Goldich, variation in volcanic suites would cause variation in the nature of the mineralization within a single metallogenetic region, or in regions belonging to different metallogenetic epochs. As a result, an area characterized by andesitic or basaltic vulcanicity over a long period of time might appear as a "copper region" through several metallogenetic epochs. On the other hand, vulcanicity might vary from basaltic to rhyolitic during one period of sedimentation, yielding a region of contemporaneous but greatly varying ores. A number of such results are clearly possible.

(6) It seems possible that, with some orebodies of this type in other regions, the stratigraphical associations are similar to those described, but are not so apparent, so that their significance has not been investigated. It is likely, for instance, that much volcanic matter may be bound up in huge thicknesses of material loosely labelled "shale." It is likely, too, that because such orebodies have not formed *in* limestone (i.e., as replacements) but only in the same locality, the importance of the limestone has not been recognized. It would also be interesting to know how many of the porphyries associated with mineralization are really silicified pyroclastic formations.

It is recognized that, as limestones develop in environments other than those of island arcs, e.g., in stable shelf areas, deposits of marine iron sulphide may occur unaccompanied by volcanic rocks. Such iron sulphide-rich sediments would, however, inevitably be involved in the folding of the sedimentary pile and might very possibly act as receptive hosts for metallic ions travelling in hydrothermal solutions derived from contemporaneous igneous intrusions. The localization of sulphides in this way might provide a reasonable solution to the following problems:

(a) the nature of the ore-forming fluid—the transport of sulphides in aqueous solutions has always been a problem in ore genesis as the extremely low solubility of these substances has required the assumption of enormous volumes of ore solution. Further, Fenner (18) has put forward very convincing arguments, strongly supported by vulcanological evidence, suggesting that the metals leave the igneous source as halides, not sulphides. If the sulphur of the orebodies were of sedimentary origin, and if the metals were derived from magmas as volatile and highly soluble chlorides, the problems of solubility of the ore minerals and volume of ore-forming fluid would not arise.

(b) progressive increase in cation/anion ratios—it has been recognized for some time, and commented upon particularly by M. C. Bandy (3), that there is a progressive increase in the ratio of the metallic radicle to the nonmetallic radicle (principally sulphur) in almost all parageneses. If the sulphur of a deposit is of sedimentary origin and hence, at the time of hydrothermal activity, fixed in amount, and if metallic ions are constantly added, it is clear that a constant quantity of sulphur would have to be shared by an ever increasing number of metallic ions. Hence as further metallic ions found their way into the lattices of already existing minerals, each new mineral so formed would contain a greater proportion of the metallic radicle than the one preceding it.

It is realized fully that many of the thoughts put forward require much

further testing before their application as general principles can be seriously contemplated. If some orebodies do originate in the manner outlined, then they should be found along the sites of many of the ancient island arcs and shelf areas—perhaps even those as old as the Precambrian—in different parts of the world. It has occurred to the writer that several well-known orebodies in Australia, and also some in other parts of the world, may very well be of this type; as he has only a superficial knowledge of these deposits, however, it is felt that it would be presumptuous to pronounce upon them. It is left to those who are well acquainted with them to decide whether the association of ore, carbonate-bearing sediments and, in some cases, pyroclastic rocks and porphyries, can be satisfactorily explained by the sequence outlined.

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IGNEOUS INTRUSIONS AND METAMORPHISM IN SOME PHOSPHATIC ROCKS OF SOUTHWESTERN MONTANA

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ABSTRACT

Exploration work to locate commercial grade phosphate rock and phosphatic shale deposits has been going on in southwest Montana for several years. Geologic mapping has resulted in finding four locations where sills, dikes, and stocks intrude or cut off the phosphate-bearing beds of the Phosphoria formation (Permian). The metamorphic effects, or lack of them, produced in the phosphatic sedimentary rocks by intrusions are of commercial and scientific interest.

In three of the areas, there have been no detectable changes in the phosphate minerals resulting from the intrusions, although the sedimentary rocks have been indurated. At the remaining area, Fleecer Mountain, the phosphatic rocks have been indurated, bleached from dark gray and black to light gray, and collophane and francolite minerals have been converted to colorless, very fine-grained apatite. Some phosphatic material has migrated. Megascopic veinlets filled with francolite developed in shale,

and microscopic quartz veinlets containing some apatite grains formed in phosphatic shale

Chemical analyses made on igneous rocks collected from the dikes, sills, and stock do not show an excess of P_2O_5 over that present in average igneous rocks of similar types.

INTRODUCTION

Purpose of Study.—For several years there has been intensive geologic mapping of the Phosphoria formation (Permian) in southwestern Montana. During this period, there has been much speculation by the numerous geologists working with the Phosphoria formation as to the metamorphism that would be encountered in the phosphatic shale and phosphate rock where they have been intruded by sills and dikes, or cut off by stocks and batholiths; and also, whether the intrusives would be enriched in apatite or other phosphate-bearing minerals.

Exploration work, during the past two years, has resulted in finding two places where sills have been emplaced in the Phosphoria formation and one place where the formation has been cut off by a stock. In addition, mining operations at the Maiden Rock Mine, near Melrose, Montana, have exposed a dike and a sill in the Phosphoria formation. These occurrences are at or near the southern edge of the Boulder batholith—one in Beaverhead County, two in Silver Bow County, and one in Madison County.

This study has a two-fold purpose: (1) to determine the metamorphic effects produced in the phosphatic shale and phosphate rock by the intrusives, and (2) to determine if the igneous rocks show evidence that phosphatic material had been assimilated.

In each of the four localities the surface geology was mapped in detail; the phosphate-bearing zone of the Phosphoria formation was measured, and hand specimens representing the lithologic units were collected for petrographic study; most lithologic units were sampled and analyzed for phosphorus pentoxide (P_2O_5); and hand specimens of the igneous rocks were collected across the intrusive bodies for petrographic study and for chemical analyses of phosphorus pentoxide (P_2O_5).

Previous Work.—The phosphate deposits of the Melrose area were described by Gale (5), and by Richards and Pardee (13). H. W. Peirce (12) did detailed mapping of a small area near the Maiden Rock Mine. Steven P. Theodosis mapped the Melrose area in detail in 1951–52 but his work has not been published. Geologic reports of the Highland Mountains have been made by Weed (20), Winchell (21), Sahinen (15), and Cass (3). The geology of the South Boulder Canyon area has been reported on by Peale (11), Tansley and others (17), Berry (2), and Barnes (1). These men did not study the phosphatic shales and phosphate rocks of the Phosphoria formation for metamorphic effects resulting from the intrusion of igneous rocks.

Terminology.—Most of the following definitions of rock and mineralogy terms as used in this study were taken from a report by the writer (9).

Shale: a rock composed dominantly of detrital mineral grains ranging from 1/256 to 1/16 mm in diameter and which may or may not have fissility parallel to the bedding.

Phosphate rock: a rock composed of 14 percent or more of P_2O_5. The P_2O_5 generally occurs as collophane. Other single minerals, or constituents, generally make up less than 30 percent of the total composition (Fig. 2).

Collophane: "Collophane" is used by McConnell (10), and Frondel (4), as a designation for the submicrocrystalline fluorapatite which is the dominant constituent of the western phosphate rocks.

Francolite: "Francolite" is used for the microcrystalline variety of fluorapatite (Fig. 6) that is commonly associated with collophane in this rock (10).

Ovule: "Ovules" refers to the phosphatic pellets that lack concentric structure (Fig. 2, 3).

Ovulitic texture: "Ovulitic texture" refers to the texture of those rocks composed of phosphatic ovules.

Oolite: "Oolite" refers to those ovules that have concentric banding (Fig. 12).

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REGIONAL GEOLOGY

Precambrian metamorphic rocks and the Belt series, Paleozoic, Mesozoic, and Tertiary sedimentary rocks, and Tertiary intrusive and extrusive rocks, are exposed in Beaverhead, Silver Bow, and Madison Counties, Montana, and in the vicinity of the small areas considered in this paper.

The Mesozoic and older formations are exposed in truncated anticlines, synclines, and fault blocks within generally north and northeast trending mountain ranges. Thrust faults and high angle normal faults have increased the complexity of the structural pattern. The Boulder batholith, dikes, and sills were intruded into the deformed sedimentary rocks. Slightly deformed Tertiary sedimentary and extrusive rocks unconformably overlie the older rocks.

Segments of the Phosphoria formation are exposed in the limbs of folds and in fault blocks, and some of these segments occur as roof pendants on the edge of the Boulder batholith. Dikes and sills occur in the Phosphoria formation in the roof pendants as well as at distances of several miles from the known border of the batholith.

The phosphatic shale and phosphate rock, of present commercial interest

in southwest Montana, occur on the south and west border of the Boulder batholith. In working out the structural geology of these phosphate deposits, it has not been necessary to study the formations older than the Madison limestone (Mississippian) because generally it is the oldest formation exposed by erosion.

The stratigraphic section generally consists of the Madison limestone (Mississippian), Amsden formation (Upper Mississippian–Lower Pennsylvanian), Quadrant quartzite (Pennsylvanian), Phosphoria formation (Permian), Dinwoody formation(?) (Lower Triassic), and Kootenai formation (Lower Cretaceous). In the South Boulder Canyon area, Madison County, the Jurassic Ellis formation is present and the Dinwoody(?) formation is absent.

In the Dell area, Beaverhead County, Montana, the Phosphoria formation has been divided into five mappable units designated as Members A, B, C, D, and E in ascending order (8). North of Dell these members tend to become thinner. North of Melrose, Montana, Members A and B are not present, and in the South Boulder Canyon area the Phosphoria formation cannot be divided into members. In the Melrose area Member C consists of dolomitic carbonate rock; Member D consists of shale, phosphatic shale, and phosphate rock; and Member E consists of chert and minor quartzite.

Petrographic study of the shale, phosphatic shale, and phosphate rock of southeastern Idaho, shows these rocks to have a relatively small suite of minerals (9). The shale consists of detrital quartz grains and muscovite flakes (mostly in the silt size), clay minerals, and organic matter. Collophane may or may not be present. The phosphate rock consists dominantly of collophane with minor quartz, clay minerals, and organic matter (Fig. 2). The gradual increase in collophane accompanied by a decrease in the quartz and other minerals produces a series of rocks that range from shale through phosphatic shale, shaly phosphate rock, and phosphate rock.. Rocks in the outcrops, or near the surface, range in color through shades of gray, brown, and black. Light colored phosphate rock generally has some francolite developed in and around the collophane ovules. From a previous study of phosphatic rocks (9), the writer believes that francolite has developed as a result of crystallization of the submicroscopic crystalline collophane during the weathering process, and therefore its presence in the rocks of this study is not indicative of contact-metamorphism.

Metamorphism in the rocks of Member D of the Phosphoria formation resulting from the deformation of the region has been slight. In some closed folds the shale and phosphatic shale have been indurated to hard, brittle rock.

THE HIGHLAND MOUNTAIN AREA

This area is located about 15 miles south of Butte, Montana (Fig. 1) in the western part of the Highland Mountains and is in secs. 28–29, 32–33, T. 1 N., R. 8 W. (Fig. 4). The area is accessible by road from U. S. Highway No. 91 near Beaudines, Montana.

Geology.—Sedimentary rocks of Paleozoic and Mesozoic age, exposed over several square miles, remain as an elongate roof pendant upon an extensive quartz monzonite which is part of the Boulder batholith. The roof pendant (Fig. 4) appears to be the southwest limb of a former northwest trending syncline which has been complexly deformed by faulting and minor folding (3). Locally andesite sills and dikes are common.

The stratigraphic section includes all of the formations from the Madison limestone to the Kootenai formation. These formations, exposed for 2½ to 3 miles, trend northwest with strikes ranging from east-west to N. 15° W. and dip 30 to 40° north and northeast.

The rocks of the above formations show some metamorphism resulting from intrusion of the quartz-monzonite (3). Those rocks next to the intrusive are more severely metamorphosed than those along the center of the roof pendant.

FIG. 1. Index map of western Montana showing the location of the small areas described. The crosses mark the area location and are identified as: X_3—Highland Mountain area; X_5—Fleecer Mountain area; X_4—Maiden Rock Mine area; and X_5—South Boulder Canyon area.

In the outer zone, carbonate rocks have been changed to marble and locally contain silicate minerals; shale and siltstone have been converted to argillite and hornfels; and sandstone and conglomerate have been changed to quartzites. The shale and phosphate rock of the Phosphoria formation located along the central area of the roof pendant and protected both above and below by thick quartzites have been somewhat indurated but are readily recognized.

Petrology of the Phosphatic Rocks.—The Phosphoria formation (Fig. 4), in the Highland Mountains, consists of three members that can be correlated with Members C, D, and E of the Melrose area to the southwest. Member C consists of marble; Member D consists of shale, phosphatic shale, and phos-

phate rock; and Member E consists of quartzite. The stratigraphy of the Phosphoria formation, as measured at the site of Trench A, is given in the following section; a stratigraphic section of Member D, Trench B, is given also.

The shale, phosphatic shale, and phosphate rock of Member D were subjected to folding and faulting prior to the intrusion of the quartz-monzonite and the andesite sills. Thus, the extra hardness and brittleness of the rocks of Member D may be the result of deformation as is the case in the Melrose area; also, it might be due to the intrusion of the quartz-monzonite, the intrusion of the sills, or a combination of all three.

The rocks of Member D, Trench B, were studied in thin section because the zone was much better exposed than in Trench A, and the andesite sills are somewhat thicker.

Section at Trench A (NW¼NE¼ sec. 32, T. 1 N., R. 8 W.). Measured by W. R. Lowell, L. F. Rooney, and W. E. Fowler. Thickness calculated from horizontal and slope measurements and dip of beds. Attitude of beds N. 65° W., 35° N. Grab samples were taken for chemical analyses. Color designation according to Rock-color chart distributed by National Research Council, 1948.

	Feet
Dinwoody(?) formation (lower Triassic) unmeasured	
Phosphoria formation (Permian):	
Member E:	
Quartzite: light gray and light pink, medium- and coarse-grained	140.0
Member D:	
8. Shale: mostly cover, black shale chips present	3.0
7. Shale: dark gray, hard, brittle, chunky, carbonaceous(?), phosphatic	3.0
6. Andesite sill: weathered to clay, light brown and olive gray	4.0
5. Shale: like unit 7	9.0
4. Phosphate rock: dark gray, hard, brittle, ovulitic texture, carbonaceous(?)	8.0
3. Limestone: gray, hard, finely crystalline	0.5
2. Shale: dark gray, hard, brittle, carbonaceous(?) phosphatic	7.0
1. Andesite sill: weathered to clay, porphyritic, white phenocrysts as much as 6 mm in diameter and 10 mm long	8.0
Apparent total thickness shale and phosphate rock	30.5
Apparent total thickness of andesite sills	12.0
Member C:	
2. Marble: medium gray, medium and coarsely crystalline; 0.5 foot thick, white quartzite near middle	43.0
1. Andesite sill(?): interval covered, but andesite exposed in Trench B; calculated thickness	78.0
Quadrant quartzite (Pennsylvanian) unmeasured	

Section of Member D, Phosphoria formation, Trench B (SE¼NE¼ sec. 32, T. 1 N., R. 8 W.). Measured by W. R. Lowell. Thickness measurements calculated from horizontal measurements and dip of beds. Attitude of beds N. 60° W., 35° N. Chip samples were taken for chemical analyses.

	Thickness in feet
Phosphoria formation	
Member E: quartzite unmeasured	
Member D:	
6. Shale: dark gray, hard, brittle, carbonaceous(?), slightly phosphatic; sharp contact with sill below	5.0
5. Andesite sill: deeply weathered, altered to clay, small white phenocrysts in olive gray matrix, sharp contact with underlying phosphate rock	9.0
4. Phosphate rock: black, hard, brittle, ovulitic texture apparent in some zones, contains many irregular porous areas, carbonaceous(?); sharp contact with sill below	12.5
3. Andesite sill: deeply weathered, altered to clay, large white phenocrysts in medium gray and olive gray matrix; sharp contact with underlying phosphate rock	8.5
2. Phosphate rock: similar to unit 4	3.5
1. Shale: dark gray, hard, brittle, some ovules present, carbonaceous(?)	6.5
Apparent total thickness of shale and phosphate rock	27.5
Apparent total thickness of andesite sills	17.5
Member C:	
2. Marble: medium gray, coarsely crystalline, calculated thickness	40.0
1. Andesite sill: covered; bulldozer trench has exposed unaltered andesite fragments: medium gray, hard, porphyritic with white phenocrysts in dark gray, aphanitic matrix, calculated thickness	75.0
Quadrant quartzite (Pennsylvanian) unmeasured	

Unit 6 is dominantly black shale, but the basal six inches consists of alternating thin zones of shale and phosphate rock. The shale portion consists of angular quartz grains embedded in dense black matrix which is probably carbonaceous matter. Some phosphatic fossil fragments are present. The shale, in thin section, is similar to shales in the Melrose area. A freshly broken surface of a specimen of phosphate rock from the basal zone, next to the sill contact, has the appearance of a breccia in that it is made up of irregular medium-gray and black areas. The contacts between black and gray areas are sharp. In thin section, the black areas consist of gray collophane ovules in which francolite has developed to some extent. The francolite portions show wavy extinction under crossed nicols. The matrix is dense black, and detrital quartz grains (as much as 0.10 mm) are irregularly dispersed in it. The gray areas consist of francolite-collophane ovules but the matrix has been completely replaced by quartz having the appearance of vein quartz (14). The detrital quartz grains in the matrix apparently have not been affected and stand out from the introduced quartz both under crossed and uncrossed nicols. Quartz has replaced fossil fragments and some ovules but the contacts between quartz and most of the collophane-francolite ovules are remarkably uniform (Fig. 3). Microscopic quartz veinlets transect the dark areas and cut across ovules and matrix alike. The noticeable change in unit 6 is the introduced quartz in the basal few inches above the andesite sill.

A chemical analysis of a sample representing nearly equal sized fragments collected from each layer indicates that unit 4 is good phosphate rock. The specimens collected show ovulitic texture. The rock is made up of collophane ovules with quartz grains (as much as 0.12 mm) enclosed in ovules and disseminated in the matrix. Some thin beds, as much as 0.5 inch, of phosphatic shale are present in the basal part of the unit. The top and base of unit 4 in contact with sills (units 3, 5) are essentially unaltered. The collophane ovules and matrix, under crossed and uncrossed nicols, remain black and are cut by several microscopic quartz veinlets. A few detrital quartz grains show the addition of secondary quartz but this is a fairly common occurrence in phosphate rocks from other areas. The shaly layers, near the base, are similar to those of unit 6 at the top of the section and do not show signs of alteration.

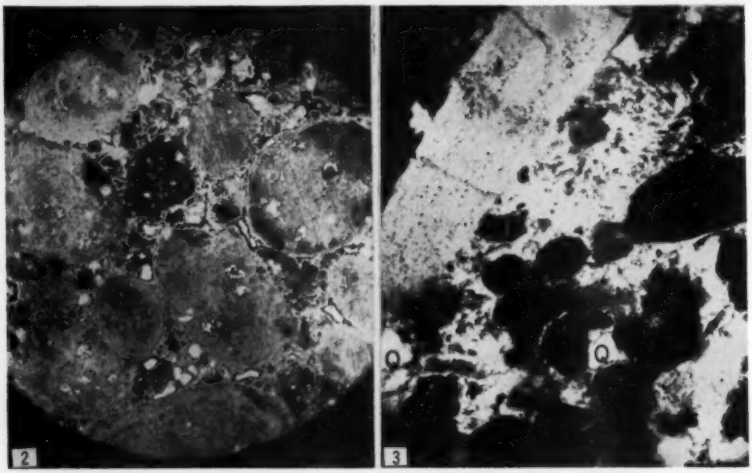


FIG. 2. (left). Phosphate rock; collophane ovules bordered by thin crusts of francolite; quartz grains (white blebs); polarized light; 50 ×. Melrose area.
FIG. 3 (right). Phosphate rock; collophane ovules (black); quartz (white) has replaced matrix and fossil fragments (upper left); detrital quartz grain (Q); polarized light; 75 ×. Higland Mts.

In thin section, unit 2 is medium gray phosphate rock consisting almost entirely of ovules and minor detrital quartz. The ovules show irregular patterns of gray and black color. The black areas remain dark under crossed-nicols. The gray areas consist of francolite. Quartz grains with secondary growth rims were not observed, but microscopic quartz veins are present.

Unit 1 is a shale consisting of detrital quartz (silt size range) and minor muscovite flakes embedded in a black carbonaceous(?) matrix. The quartz grains and the muscovite flakes do not show evidence of having been altered.

Petrology of the Igneous Rocks.—The stratigraphic sections show three sills that have been intruded between the top of the Quadrant quartzite and the

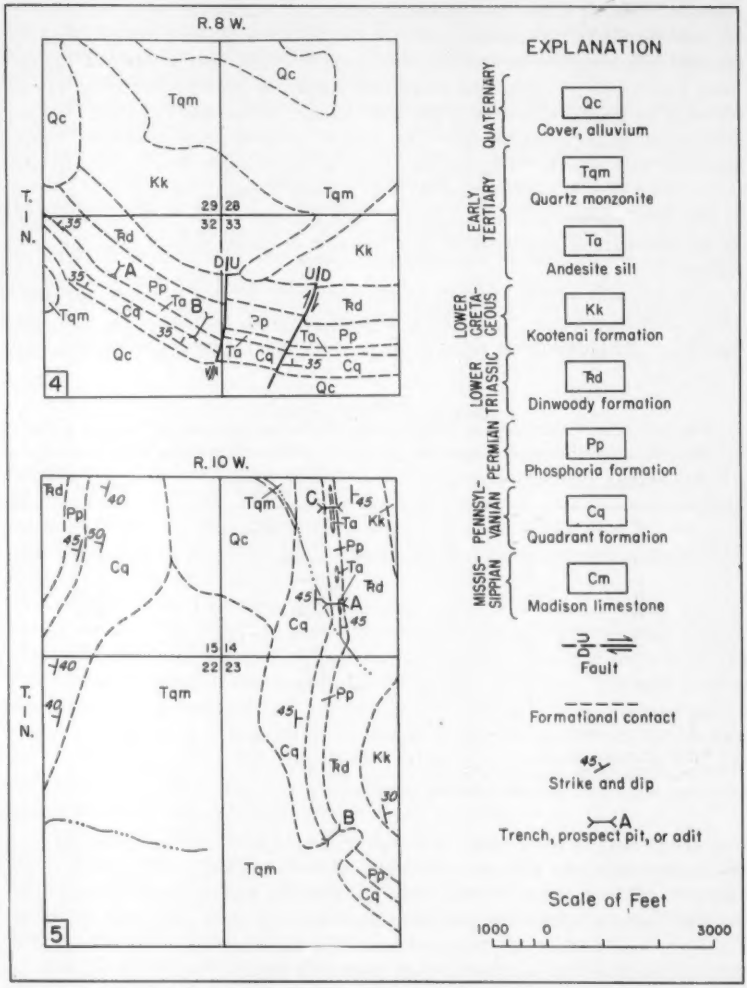


FIG. 4. Highland Mountain area. FIG. 5. Fleecer Mountain area.

base of Member E. The sills did not show at the surface before the bulldozer trenching project.

Unaltered porphyritic andesite rocks were exposed in the south end of Trench B (Fig. 4) that crosses a covered interval that is of uniform width for about one mile westward along the strike of the beds. This entire interval,

between Member C and the Quadrant quartzite, is thought to be occupied by an andesite sill that is approximately 75 feet thick. Cass (3) thought that this interval was occupied by another shale zone as is the case in parts of Beaverhead County (7). The rock fragments consist of zoned labradorite phenocrysts in an aphanitic matrix of andesine laths. Albite and Carlsbad twinning are present in the phenocrysts. The matrix contains some secondary biotite, actinolite and quartz. The quartz occurs as microscopic veinlets and related pods, which may be replacement bodies or cavity fillings. A chemical analysis of this rock showed a silica content of 58.7 percent. The rock was classified as an andesite on the basis of the andesine feldspar matrix and the silica content (18).

The two sills within Member D are completely altered to montmorillonite. Large white phenocrysts, showing crystal outlines, remain in a dark gray matrix. The phenocrysts show zoning. Secondary quartz veinlets and pods

TABLE 1

THE LOCATION OF SPECIMENS IN ANDESITE SILLS* AND THE ANALYSIS OF P_2O_5 FOR EACH

Trench	Sill	Location of specimen in sill	Percent of P_2O_5
B	1	near top	0.26
B	2	upper contact	0.25
B	2	middle	0.22
B	2	base	0.44
B	3	top	0.18
B	3	base	0.63
A	2	top	0.18
A	2	base	0.23
A	3	top	0.23
A	3	base	0.22
Average content			0.28

* The sill below Member C is referred to as No. 1.
The lower sill in Member D is referred to as No. 2.
The upper sill in Member D is referred to as No. 3.

also are present in these sills. Chemical analyses of specimens collected from the lower and upper sills show 56.9 and 56.3 percent silica respectively. Because the silica content is in the range for andesite these sills are so classified.

The andesite specimens collected from the sills were analyzed chemically for P_2O_5 to determine if phosphatic material had been assimilated. The results of the chemical analyses are tabulated in Table 1. The P_2O_5 content for the specimens is fairly uniform; only those from the lower contacts of sills 2 and 3, Trench B, contain more than the others. In order to determine what might be termed the normal percentage of P_2O_5 for andesites in other areas the following analyses are offered. Washington (19) lists 196 analyses of P_2O_5 for andesites in which the percentage of P_2O_5 ranges from 0.05 to 1.33 with an average of 0.30. Jurkovic (6) lists two analyses for andesites of 0.24

and 0.25% P_2O_5. Shelton (16) gives one analysis of 0.28% and one of 0.42% P_2O_5 for andesites in the Los Angeles Basin. Hence, it would seem that the P_2O_5 content of the andesite sills in Member D is about normal, and that the sills did not assimilate phosphatic sediments.

Conclusions.—The evidence for alteration in the shale and phosphate rock consists of induration and the presence of secondary quartz. Induration of similar rocks in the Melrose area has resulted from deformation, which also has affected these rocks. Quartz veinlets and replaced areas are present in the andesite sills as well as in shale and phosphate rock and thus appear to be younger than the andesite sills. Carbonaceous matter(?) may have been converted to fixed carbon by the heat of the intrusive to produce the black color of the phosphate rocks.

The lack of contact metamorphism in the shale and phosphate rock beds and the sharp contacts with the andesite sills indicate that the sills were injected at fairly low temperature and without assimilation of phosphatic material.

FLEECER MOUNTAIN AREA

The Fleecer Mountain area (Fig. 1) is located 6 miles N. 30° W. of Divide, Silver Bow County, Montana. The area is included in secs. 14, 15, 22, and 23, T. 1 N., R. 10 W. (Fig. 5), and is located west and southwest of the crest of Fleecer Mountain (elevation 9,460 feet). The area is accessible by jeep from U. S. Highway No. 91 by a road that branches west at Beaudines, Montana.

Geology.—The Paleozoic and Mesozoic sedimentary rocks of the Fleecer Mountain area (Fig. 5) have been folded into the large north trending Fleecer Mountain anticline. Quartz monzonite has been intruded into the core of the anticline and generally ascended to the Quadrant quartzite. The east limb of the anticline is a roof pendant completely surrounded by the intrusive which is part of the Boulder batholith. A quartz monzonite apophysis cuts across the Quadrant quartzite, Phosphoria formation, and part of the Dinwoody formation in the SW¼ sec. 23. A lamprophyre sill is exposed in a prospect tunnel at site A and in a dozer trench at site C (Fig. 5).

Petrology of the Phosphatic Rocks.—The Phosphoria formation consists of the same three members as already described for the Melrose area. The primary difference is that Member C consists of very fine-grained quartzite and some thin beds of marble. The stratigraphy of Member D and the position of the lamprophyre sill are given in the following section.

The phosphatic shales and phosphate rock samples collected from the prospect adit (site A, Fig. 5) for determination of P_2O_5 content show several significant changes that have not been observed in similar rocks from the other areas: the changes include (1) bleaching of dark colored rocks to very light gray; (2) changing of collophane and francolite to apatite; (3) migration of phosphatic material and quartz; and (4) partial to complete destruction of ovulitic texture.

Stratigraphic section of Member D. Measured by H. Johnson and R. Gale in prospect tunnel (site A, Fig. 5). Beds strike N.–S., dip 45° E.

	Thickness in feet
Dinwoody formation (lower Triassic)	
Phosphoria formation (Permian):	
Member E: chert, unmeasured	
Member D:	
13. Phosphate rock: gray, some nodular areas	1.4
12. Phosphate rock: light greenish gray, chalky and clayey texture	1.0
11. Shale: light greenish gray, limonite stained, hard, disseminated ovules, phosphatic	0.6
10. Lamprophyre sill: light gray and pinkish gray, limonite stained, aphanitic, much disseminated pyrite	2.8
9. Phosphate rock: light gray, weathers yellowish gray, hard	0.2
8. Shale: medium light gray, weathers light greenish gray, limonite stain	0.6
7. Shale: very light gray, weathers pale yellowish brown, clayey texture	0.3
6. Phosphate rock: pinkish gray and light greenish gray, very fine-grained, some areas of ovulitic texture	0.2
5. Phosphate rock. medium gray, limonite stain, very fine-grained, some areas of ovulitic texture, calcareous	2.0
4. Shale: dark gray, hard, phosphatic	1.1
3. Phosphate rock: dark gray, hard, shaly, carbonaceous(?), ovulitic texture	5.2
2. Shale: dark gray, soft, phosphatic	1.6
1. Phosphate rock: dark gray, hard, shaly, ovulitic texture, carbonaceous(?)	3.8
Total thickness	20.8
Member C: quartzite and chert, unmeasured; malachite stain in fractures of the uppermost bed at this place resulted in the prospect adit.	
Quadrant formation (Pennsylvanian)	

The phosphate rocks of units 12 and 13 are similar except in color. In thin sections the rock is yellowish gray with much limonite stain, whereas light gray phosphate rocks from other areas generally are brownish to dark gray in thin sections. The ovulitic texture is well preserved. In the ovules collophane is dominant although much francolite has been developed. Detrital quartz grains do not show secondary addition of quartz. Carbonaceous matter(?) and clay minerals form a brown opaque matrix between the ovules.

The shale of unit 11, in thin section, appears the same as the shale of the Melrose area. Laminae are well developed, and collophane ovules apparently are unchanged. Small irregular areas of francolite appear to have replaced some of the shale but this is not uncommon in shales from other areas. Microscopic veinlets of quartz and apatite are a significant feature in unit 11. A shale specimen collected from the same stratigraphic position from the dozer trench at site C (Fig. 5) contains visible veinlets. The vein mineral was identified in this section as francolite. The optical properties include concentric zoning and needle-like radiating crystals (Fig. 6) which together display

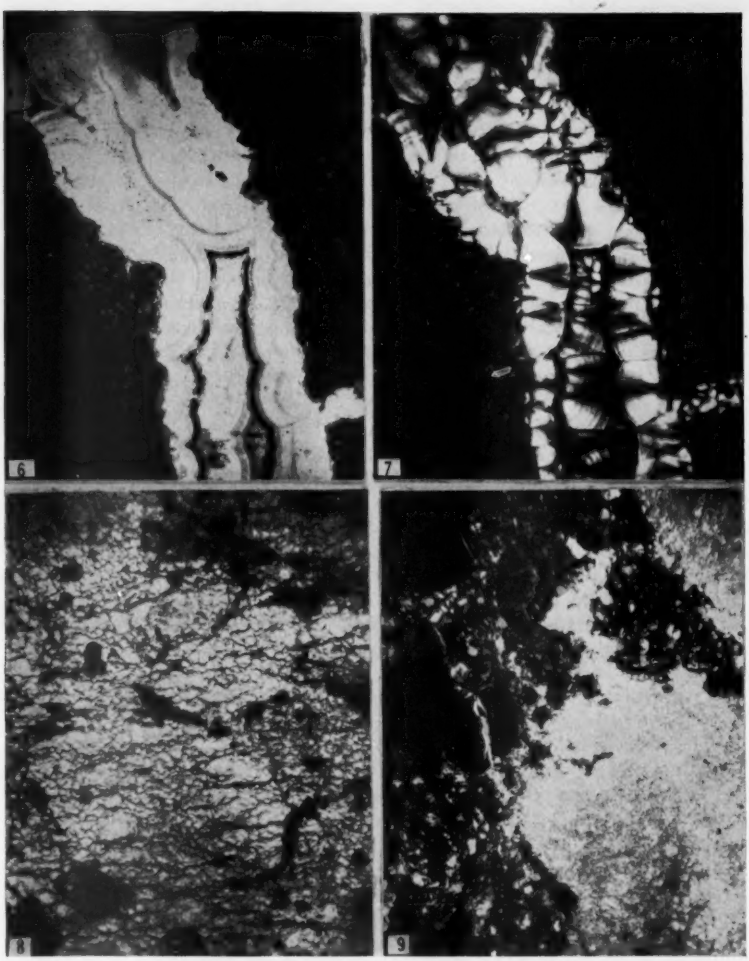


FIG. 6 (left). Francolite veinlet in shale. Polarized light; 75 ×. Fleecer Mt.
FIG. 7 (right). Same as Fig. 8; crossed nicols; polarization figures well developed; 75 ×. Fleecer Mt.
FIG. 8. Phosphate rock: ovules almost destroyed; apatite grains make up white areas; carbonaceous matter (black); 75 ×. Polarized light. Fleecer Mt.
FIG. 9. Contact of phosphatic shale and dike rock in thin section; 50 ×. Polarized light. Maiden Rock Mine.

excellent polarization or spherulitic crosses (Fig. 7); wavy extinction under crossed nicols; uniaxial (−); and moderate index of refraction.

A thin gradational boundary is present between the lamprophyre sill (unit 10) and the upper shale (unit 11). A thin section of the contact zone shows shale grading into plagioclase rock.

The 3.3 feet of rock (units 5–9) below the sill is dominantly phosphate rock. These rocks are very light gray in hand specimen but are white with some limonite streaks and blebs in thin sections. The ovulitic texture is almost completely destroyed (Fig. 8). The collophane and/or francolite of the ovules has been converted to small irregular grains of apatite. The grains are transparent in polarized light, gray under cross-nicols, and all have a moderate index of refraction. A few of the larger grains gave good uniaxial negative figures. The quartz grains are rounded to angular but apparently have not been altered. The carbonaceous matter(?), which produces the dark color of the normal phosphatic rocks, has been removed except for the small amount remaining between grains (Fig. 8).

TABLE 2

ANALYSES OF QUARTZ MONZONITE SPECIMENS

Sample No.	SiO_2	Al_2O_3	Fe_2O_3*	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	Total
L1	63.4	16.7	4.92	4.65	1.80	3.45	2.80	0.45	0.29	98.46
L2	64.2	15.9	4.40	4.34	2.04	2.62	4.56	0.41	0.18	98.65
L3	63.4	17.6	3.23	5.19	2.42	3.59	3.70	0.30	0.21	99.64
L4	64.3	17.4	4.86	5.68	1.66	3.17	1.68	0.35	0.24	99.34
L5	65.6	16.8	4.63	4.47	1.56	3.66	2.66	0.41	0.21	100.00
L6	65.6	15.5	4.12	4.14	1.90	3.12	3.76	0.41	0.19	98.74
Average	64.4	16.6	4.36	4.74	1.60	3.27	3.19	0.39	0.22	98.71

* Includes FeO and Fe_2O_3.

The rocks of units 1–4 inclusive have the dark gray colors normal to phosphatic rocks of this region and do not appear to have been altered.

Petrology of the Igneous Rocks.—The quartz monzonite stock in the core of the anticline (Fig. 5) is medium gray color, medium-grained, equigranular, and unweathered. The essential minerals are orthoclase, oligoclase, and andesine. The latter two minerals occur as zoned phenocrysts with andesine in the cores. Hornblende is the important accessory mineral, and some apatite grains are present. Quartz makes up approximately 5–10 per cent of the rock. Chemical analyses of six hand specimens of quartz monzonite, collected in the map area, are given in Table 2.

The P_2O_5 content in the hand specimens ranges from 0.18 to 0.29 percent with an average of 0.22 percent. Washington (19) lists 42 analyses of P_2O_5 for quartz monzonites in which the range is 0.01 to 0.60 percent with an average of 0.25 percent. It would seem that the quartz monzonite where exposed on the west and south sides of Fleecer Mountain does not contain an excess of P_2O_5.

The detailed areal geology of T. 1 N. and T. 1 S. completed, but not pub-

lished, by George T. Moore and Steven D. Theodosis respectively shows that approximately four linear miles of the Phosphoria formation may have been "engulfed" by the quartz monzonite. The east limb of the Fleecer Mountain anticline (Fig. 5), prior to intrusion, apparently was once continuous with the northeast striking and southeast dipping Paleozoic and Mesozoic formations in sec. 9, T. 1 S., R. 10 W. If this interpretation is correct then several million tons of phosphatic shale and phosphate rock were assimilated or stoped by the quartz monzonite. It is possible that these sedimentary rocks were faulted and pushed aside by the intrusive and later removed by erosion, but the geologic field evidence does not support this suggestion.

The question arises as to what has happened to the assimilated or stoped phosphatic material? Did convection currents in the magma chamber transport the P_2O_5 enriched magma, or stoped blocks, to depth where erosion has not yet exposed it or did it move upward where it has been eroded? Possibly the phosphatic material was disseminated widely in the magma before final crystallization and the addition is not apparent.

The quartz monzonite apophysis, SW¼ sec. 23 (Fig. 5), is not exposed at the surface due to cover although its position is clearly shown on the aerial photograph of the area. The apophysis is approximately 400 feet wide and 1,000 feet long. Quartz monzonite fragments are present along the trend of the intrusion. An old prospect pit, now caved, is located at or near the phosphatic shale and phosphate rock-igneous contact (site B, Fig. 5).

Four rock types are abundant in the excavated material piled around the pit. Two of these are metamorphosed sedimentary rocks clearly belonging to Member C of the Phosphoria formation. Another type, the most abundant in the dump, is from the contact metamorphic zone and is composed of magnetite and antigorite in about equal amounts. The remaining type is unweathered quartz monzonite. The latter specimens probably were formed at or near the edge of the apophysis, certainly they were formed no more than 200 feet from the contact, and they should show the effects of contamination if phosphatic rock had been assimilated.

Chemical analyses for P_2O_5 were made on four hand specimens of quartz monzonite from the pit. The analyses showed 0.13, 0.13, 0.15, and 0.18% P_2O_5 which is somewhat lower than the P_2O_5 analyses listed in Table 2. A logical conclusion for the low P_2O_5 content is that the phosphatic rocks may have been sealed off by the development of a contact metamorphic zone and the quartz monzonite that crystallized at this place was not contaminated. Magma ascending at an earlier stage may have assimilated phosphatic rock and carried it upwards; if so, it has been removed by erosion.

The lamprophyre sill in Member D is light gray, very fine-grained, and has the composition of diorite. Andesine is the dominant mineral and occurs in laths which have labradorite cores. Minor hornblende and some quartz are present. Pyrite is abundant in the middle of the sill. Apatite grains were not observed in the thin sections although a chemical analysis showed 0.96% P_2O_5.

In a dozer trench at site C (Fig. 5) a zone of grayish yellow clay, 5 feet thick, occupies the stratigraphic position of the lamprophyre sill. The clay is

dominantly montmorillanite with minor kaolinite and undoubtedly represents the deeply weathered lamprophyre sill. The clay zone contains 0.85% P_2O_5. The lamprophyre sill contains approximately three times the average P_2O_5 content of the andesite sills in the Highland Mountain (Table 1) although it is within the range of P_2O_5 content (0.05 to 1.33 percent) cited on page 724. Thus, from analyses, it is possible some phosphatic material was assimilated by the sill.

Conclusions.—Phosphatic rocks above and below the lamprophyre still have been bleached from dark gray to very light gray; ovulitic texture has been partially to completely destroyed in some of the phosphate rock; collophane and francolite have been altered to fine-grained anhedral apatite; and some phosphatic material has migrated, at least for short distances, to form francolite veinlets and quartz-apatite veinlets.

The lamprophyre sill, in Member D, does not show an excess of P_2O_5 and apatite was not observed in thin sections. The temperature of the sill apparently was great enough to cause changes in the adjacent phosphatic rocks. The sharp contacts of the sill with the enclosing rock indicate forceful injection of the magma.

Hand specimens of the quartz monzonite stock do not show the results of having assimilated phosphatic material, although the geologic evidence indicates that several linear miles of the Phosphoria formation had been assimilated, or stoped, during the emplacement of the stock. An apophysis, or dike, from the quartz monzonite stock developed a contact metamorphic zone across part of the Phosphoria formation, but the specimens available do not show the formation of phosphatic minerals.

MAIDEN ROCK MINE AREA

The Maiden Rock mine area is located about 30 miles south of Butte, Montana (Fig. 1). The mine can be reached from U. S. Highway No. 91 by turning west on the gravel road that leaves the highway in NE¼NE¼ sec. 33, T. 1 S., R. 9 W. The mine is 1½ miles from the turn-off.

Geology.—Sedimentary rocks of late Paleozoic and Mesozoic age and early Tertiary quartz monzonite stocks, sills (?), and dikes are exposed in the vicinity of the mine. The sedimentary rocks have been folded into northwest trending anticlines and synclines which locally have been overturned to the east. Major thrust faults and longitudinal and transverse high angle faults complicate the structural geology.

The Maiden Rock Mine, NE¼ sec. 5, T. 2 S., R. 9 W. (Fig. 10), is located on the east limb of the Big Hole syncline. The sedimentary rocks in this limb strike N. 30°–40° W., and dip 35°–60° SW. Numerous tabular igneous rock bodies parallel the strike of the sedimentary rocks but some cut across the beds below the surface. A large dike, 30 to 40 feet thick, cuts the Phosphoria formation nearly normal to the strike of the beds in the SW¼ sec. 4 (Fig. 10). The main mine tunnel cuts this dike 300 feet below the surface. About one half mile south the main drift cuts another dike that angles across the phosphate rock and shale of Member D.

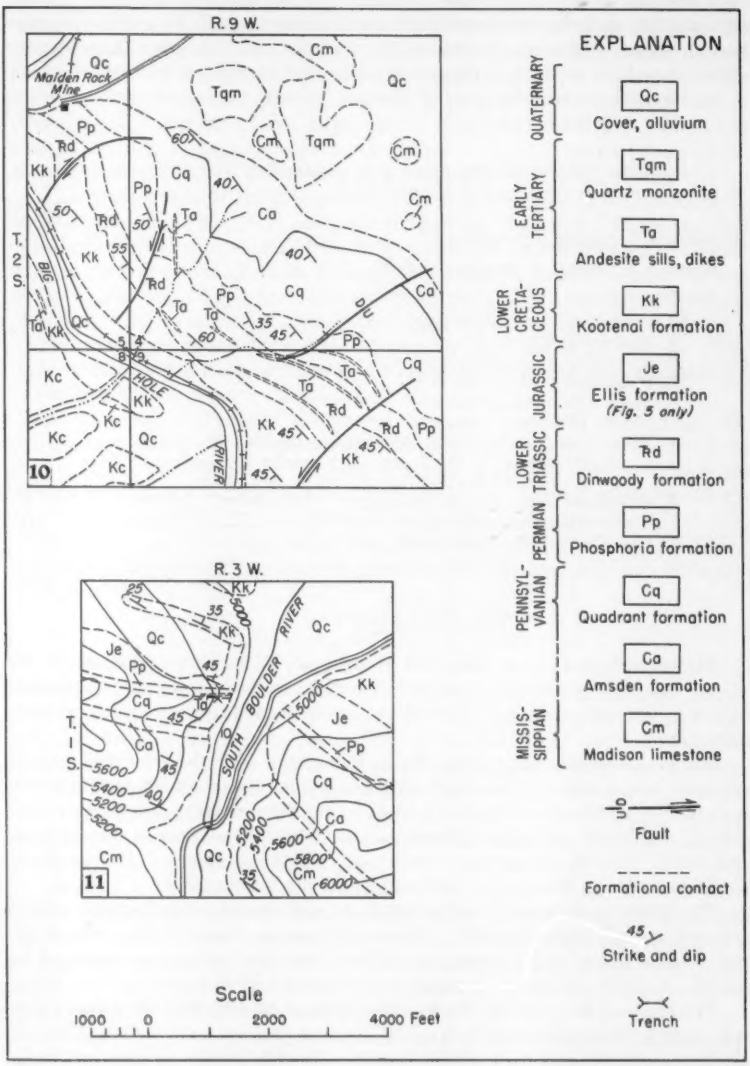


FIG. 10. Maiden Rock Mine area. FIG. 11. South Boulder Canyon area.

Petrology of the Phosphatic Rocks.—The Phosphoria formation in this area consists of three members which are designated as C, D, and E from the base upwards. Member C consists of carbonate rock; Member D consists of shale, phosphatic shale, and phosphate rock; and Member E consists of chert. A stratigraphic section for part of Member D, with the approximate position of the dike, is given below.

Stratigraphic section for the upper part of Member D, Phosphoria formation, Maiden Rock mine (sec. 9, T. 2 S., R. 7 W.).

	Thickness in feet
Phosphoria formation (Permian):	
Member E: chert of hanging wall	
Member D:	
10. Phosphate rock: dark gray	3.5
9. Shale: black	1.2
8. Phosphate rock: dark gray	1.4
7. Phosphate rock: dark gray	3.4
6. Shale: phosphatic, black	2.1
5. Shale: phosphatic, black	2.5
4. Dike: granodiorite (?); approximate position as determined by comparison of lithologies with nearby section where sill is not present; thickness could not be measured	—
3. Phosphate rock: shaly, dark gray	1.3
2. Shale: phosphatic, black	1.0
1. Phosphate rock: shaly, dark gray	0.7
Thickness of commercial zone	17.1
(Remainder of Member D not exposed)	

Metamorphic minerals were not recognized in the zone adjacent to the dike. Quartz grains do not show addition of secondary quartz, and collophane ovules in the shale do not show evidence of replacement by francolite or other minerals.

Black phosphatic shale (unit 5) is in contact with the dike where it is exposed in the mine. The shale consists dominantly of an unidentified clay mineral or minerals, with disseminated angular quartz grains, muscovite shreds, and black collophane ovules. Secondary calcite replaces clay matrix, and calcite veinlets cut across matrix and collophane ovules. The calcite is continuous across the contact with calcite in the dike rock.

Phosphate rock, unit 7, 4½ feet from the sill consists of collophane ovules and oolites and calcite cement. A few microscopic blebs of clay remain between some ovules and oolites and indicate that the matrix was replaced by calcite. Calcite-collophane contacts are uniform and sharp.

Petrology of the Igneous Rock.—The sill and dike rock at the ground surface is pale olive color, hard, fine- to medium-grained, and well weathered. Underground the rock is white with pale yellowish orange streaks and blebs of limonite. The rock is completely altered to clay minerals, quartz, and calcite. The clay minerals are montmorillonite, illite, and kaolinite in proportions of 2:1:1 respectively. Quartz grains are disseminated through the clay

minerals and calcite. Two generations of calcite are present. The first generation consists of fine-grained calcite which has replaced large areas of the clay minerals. Later calcite veinlets cut across clay and calcite areas. A few poorly defined feldspar phenocrysts have been preserved. Two chemical analyses showed 66.3 and 67.3 percent silica to be present which is slightly higher than the silica content of the large quartz monzonite mass exposed on the flanks of Fleecer Mountain to the north (Fig. 5). It is likely that the original dike rocks were close to quartz monzonite in composition (18).

The contact zone of the dike rock and shale is irregular in hand specimens and in thin section (Fig. 9). Irregular projections of altered dike rock project into the shale and projections of shale remain in the altered dike rock. Small irregular patches of black shale, incompletely replaced, remain as much as two inches within the dike rock. The nature of the contact indicates that some phosphatic shale was assimiliated by the magma. Chemical analyses for P_2O_5 in samples representing both dikes show only 0.18 and 0.22 percent. The shale remains black in color right to the contact. The magma apparently did not have sufficient heat to bleach the shale.

Conclusions.—Magma of low temperature was forcefully injected into the sedimentary rocks. Some assimilation of phosphatic material is indicated by the contact relationships but chemical analyses of altered dike rock from the contact zone do not substantiate this conclusion. Following emplacement the dike rock was altered to clay minerals which have been partially replaced by calcite. The source of the calcite may have been solution of Member C followed by redeposition from ground water in the dike and adjacent shale and phosphate rock.

SOUTH BOULDER CANYON AREA

South Boulder Canyon is located in the north end of the Tobacco Root Mountains, Madison County, Montana (Fig. 1). A good, all weather county road branches south from U. S. Highway No. 10 about six miles east of Whitehall, Montana. The county road, passing through Cardwell and Jefferson Island, follows the canyon floor southward for many miles into the mountains.

The Phosphoria formation crops out on the west side of the canyon where the road enters the main part of the canyon in sec. 10, T. 1 S., R. 3 W. A hand trench, across the Phosphoria formation, is located in the SE¼NW¼ sec. 10 and about 100 feet above the uppermost irrigation ditch.

Geology.—The stratigraphic section of the Tobacco Root Mountains includes Precambrian gneiss, schist, and the sedimentary Belt series, Paleozoic, Mesozoic, and Tertiary sedimentary rocks, and Tertiary intrusive and extrusive igneous rocks. South Boulder Canyon, trending northward, dissects the southwest limb of a northwest trending syncline (Fig. 11). The sedimentary rocks strike N. 45°–60° W., and dip 35°–55° NE.

Andesite sills are present in most of the pre-Mississippian formations but are prominent in the Middle Cambrian Wolsey shale and Upper Devonian Threeforks shale. Only one sill has been observed in the Phosphoria formation (Fig. 11). Andesite extrusives unconformably overlie part of the Kootenai formation to the north.

Petrology of the Phosphatic Rocks.—The details of the stratigraphy of the Phosphoria formation in this area and the position of the sill are given in the following section.

Section of the Phosphoria formation (SE¼NW¼ sec. 10, T. 1 S., R. 3 W.). Measured by L. F. Rooney. Beds strike N. 50° W., dip 45° N.

	Thickness in feet
Ellis formation (Jurassic) not measured.	
Phosphoria formation (Permian):	
22. Cover	2.0±
21. Chert: brown, irregular thin beds, some interbedded hard shale	9.2
20. Phosphate rock: medium gray, ovulitic	0.8
19. Shale: black, weathers medium gray	1.3
18. Chert: like unit 21	7.2
17. Phosphate rock: like unit 20	0.4
16. Shale: like unit 19	1.2
15. Phosphate rock: gray, hard, massive, ovulitic, chert nodules in base	0.5
14. Chert: brown	0.6
13. Phosphate rock: like unit 15	0.5
12. Shale: black, fissile	2.4
11. Chert: black, well-bedded	5.0
10. Limestone: medium gray, massive	4.8
9. Shale: black, fissile	2.0
8. Limestone, shale, and chert	1.4
7. Shale: black fissile	7.5
6. Phosphate rock: gray, hard, oolitic, nodules as much as 27 mm. diameter	0.6
5. Shale: moderate brown and grayish brown, platy, and thinly laminated	1.4
4. Andesite (?) sill: altered to grayish orange clay	4.5
3. Shale: like unit 5	0.6
2. Phosphate rock: like unit 6	0.7
1. Chert: black, well-bedded	4.0
Total thickness	59.1
Quadrant formation (Pennsylvanian): unmeasured.	

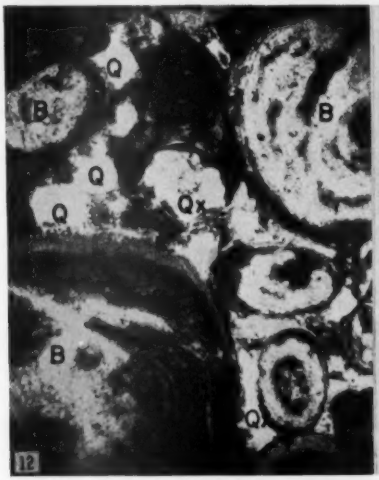
The shale, above and below the sill, is moderate brown and grayish brown in color. Some thin lenses are dark gray and these may have been the original color of the rock. The shale is hard and brittle and breaks into plates that range from 0.1 to 0.5 inch in thickness. The other shales above the sill are black and fissile. The hardness and brittleness of the shale next to the sill probably is the result of contact metamorphism.

The lower and upper shale (units 3 and 5) consist of about equal amounts of detrital quartz grains and muscovite flakes, mostly in the silt size range, embedded in clay matrix. The quartz grains are angular and do not show secondary addition of quartz. The lower shale (unit 3) contains about 5 percent of collophane ovules that range up to 1 mm in length. The quartz, muscovite, and collophane do not show any signs of alteration and in thin section (Fig. 12) are similar to shale that has not been in contact with or near an intrusive body.

The phosphate rock of units 2 and 6 range in color from light gray to

medium dark gray. In thin-section the color is yellowish brown. Collophane forms the ovules, oolites and matrix. Detrital quartz grains, in silt and small sand sizes, are enclosed in ovules, oolites, and matrix. Secondary quartz is abundant as irregular replacements of oolite centers, veinlets cutting across oolites and matrix, and as matrix replacement (Fig. 13). The secondary quartz occurs as a mosaic of microscopic grains. Calcite veinlets and irregular replacement areas cut across secondary quartz structures. Some francolite is developed within and around collophane oolites.

Petrology of the Igneous Rocks.—The sill rock is completely altered to kaolinite, montmorillonite, and quartz. It is grayish orange in color with veinlets and granules of dark yellowish brown limonite. Kaolinite is about



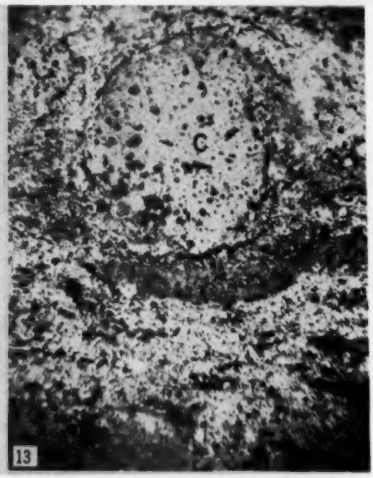


FIG. 12 (left). Phosphatic shale: collophane ovule (C); quartz and clay comprise the matrix. Polarized light; 75 ×. South Boulder Canyon.

FIG. 13 (right). Phosphate rock: collophane oolites with bleached (B) rings and irregular areas; detrital quartz grains (Q); secondary quartz (Qx); 50 ×. Polarized light. South Boulder Canyon.

twice as abundant as the montmorillonite which consists of mixed Na- and Ca-bearing layers. The sodium and calcium are interpreted as being indicative of the former presence of Na- and Ca-feldspars. A chemical analysis shows 51.4% SiO_2 in the sill rock. On the basis of the silica content and the presence of sodium and calcium the sill is thought to have been an andesite prior to its alteration. A chemical analysis of the sill rock shows 0.53% P_2O_5 which is within the normal range of phosphorus pentoxide of andesite rocks and may indicate that phosphatic material had not been assimilated.

Conclusions.—The phosphatic shale and phosphate rock from this locality, in hand specimen and in thin section, appear much like similar type rocks elsewhere. Quartz has been introduced into the phosphatic rock but the quartz

cannot be definitely related to the andesite (?) sill. The induration of the shale units next to the sill seem to be the only metamorphic effects.

SUMMARY

Geologic mapping in southwestern Montana has resulted in discovering four locations where igneous rocks have intruded the phosphatic rocks of the Phosphoria formation. Detailed study of the intrusive rocks and of the phosphatic shales and phosphate rocks was undertaken to determine if the igneous rocks had assimilated phosphatic material and to determine the metamorphic effects in the phosphatic rocks. The following conclusions were made:

(1) The andesite sills, of the Highland Mountains and South Boulder Canyon, and quartz monzonite sills (?) and dikes, at the Maiden Rock Mine, represent magma injected at low temperature into the phosphatic rocks. Phosphatic material was not assimilated, and the only metamorphism observed was induration of the adjacent rocks.

(2) The quartz monzonite stock, of the Fleecer Mountain area, assimilated or stoped several linear miles of the Phosphoria formation, but chemical analyses of the rock do not show an excess of P_2O_5 over that present in normal quartz monzonite.

(3) A quartz monzonite apophysis from the main stock developed a contact metamorphic zone across the Phosphoria formation but contact metamorphic minerals containing phosphorus were not identified. Quartz monzonite rocks formed near the contact zone do not contain an excess of P_2O_5 although apatite grains are present in the rock.

(4) A lamprophyre sill, Fleecer Mountain area, intruded into the phosphatic rock member, contains approximately three times the average P_2O_5 content of the nearby quartz monzonite. Some phosphatic material may have been assimilated but apatite was not observed in thin sections of the rock. The adjacent phosphatic rocks were bleached to light gray colors. Collophane and francolite were converted to colorless anhedral apatite grains. Some phosphatic material migrated to form veinlets. Francolite veinlets fill fractures in a phosphatic shale adjacent to the sill. A thin section of a specimen of the same shale has microscopic quartz veinlets that contain some anhedral apatite grains.

(5) Although the igneous rock specimens did not contain an excess of P_2O_5 it is possible that phosphatic material was assimilated at least by the quartz monzonite stock and transported upwards or downwards by convection currents. If transported upwards, the phosphatic enriched rock has been removed by erosion; if downwards, erosion has not yet uncovered it.

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May 27, 1955

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ORIGIN OF HEAVY MINERALS IN JAMAICAN BAUXITE

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ABSTRACT

Previous investigation of the bauxite of the Caribbean Islands has resulted in the publication of two opposing theories of origin for these deposits. (1) The bauxite represents a residual accumulation of the insoluble constituents in the White Limestone formation that underlies the deposits in Jamaica. (2) The bauxite was derived from the alteration of a volcanic ash that was deposited on the limestone. In the latter case the heavy minerals would be expected to vary in the bauxite and in the limestone. This study of the bauxite and associated formations of Jamaica shows that the bauxite and White Limestone have similar heavy mineral suites. The important feature displayed by the heavy minerals in the White Limestone is the presence of titanium in the following minerals: ilmenite, rutile, leucoxene, and titaniferous magnetite. Hence, a residual accumulation from the limestone should contain TiO_2. Moreover, the presence of titanium in the bauxite does not necessarily imply that these deposits were derived from a layer of volcanic ash. The author concludes that the probable source of the bauxite is the White Limestone formation.

INTRODUCTION

THE discovery of bauxite deposits of the terra-rossa type in the Caribbean Islands represents one of the major mineral finds in recent years. The origin of these deposits has been briefly discussed by Schmedeman (8, 9) and by Goldich and Bergquist (1, 2). Schmedeman's work covered the Jamaican deposits primarily, whereas Goldich and Bergquist were interested in the deposits of Hispaniola. As a result of these studies two opposing theories of origin have evolved.

Schmedeman (8, 9) believed that the bauxite developed as a residual accumulation of the insoluble residue contained in the White Limestone formation of Middle Tertiary (Upper Eocene to Lower Miocene) age. His theory is substantiated by at least two facts: 1) bauxite occurs exclusively on the White Limestone; 2) the White Limestone contains minor constituents that could yield bauxite in the course of lateritic weathering.

Goldich and Bergquist (1, 2) conclude from their study of the Hispaniola deposits that the limestone formation is too pure to yield the bauxite as a residual accumulation. They point out that the limestone commonly contains more than 99 percent $CaCO_3$ and less than 0.1 percent Al_2O_3. Spectrographic analysis of the limestone showed that in samples from Hispaniola the percentage of TiO_2 varies from nil to 0.0002 percent (2, p. 107). The authors state, "An x-ray analysis of a residue obtained by dissolving 50 grams of limestone in dilute acetic acid showed only a phosphate of the apatite group . . . examination of the residue with a petrographic microscope revealed no identifiable mineral other than the phosphate mineral" (2, p. 70). On the basis of

this evidence and the ratio of Al_2O_3:Fe_2O_3:TiO_2, Goldich and Bergquist propose that the parent material of the bauxite was a volcanic ash of intermediate, probably andesitic, composition.

Purpose and Scope.—The purpose of this paper is to examine the insoluble residues of the bauxite and associated formations in order to see if a correlation between the White Limestone and the bauxite can be made on the basis of heavy minerals. The occurrence of titanium minerals in the limestone is of special import to this study since their presence would eliminate the necessity of an igneous source for the TiO_2.

The area selected for this study was the St. Ann district, known also as the Claremont-Moneague district.

A discussion of the geology of the Island and a general description of the bauxite deposits are beyond the scope of this paper. These are adequately reported elsewhere, and the reader is referred to Hill (3), Sawkins (7), and Zans (12, 14) for the former, and to Goldich and Bergquist (1, 2), Hill (4), Hose (5), Schmedeman (8, 9), and Zans (12, 13) for the latter.

Acknowledgments.—I would like to express my appreciation to Reynolds Jamaica Mines, Ltd. for whom I was working during the early part of this study. I am particularly indebted to Mr. William S. Cole, Jr., Resident Manager, for his kind cooperation, and to Mr. Vincent G. Hill, former Chief Chemist, who assisted with the field work and supervised the chemical analyses of all samples used in this study. The laboratory work was supported in part by the Union Carbide and Carbon Corporation Research Fellowship in Economic Geology and their aid is gratefully acknowledged. This study was conducted in the Economic Geology Laboratory of the University of Wisconsin under the supervision of Dr. E. N. Cameron whose suggestions during the course of this investigation have been invaluable.

PETROGRAPHIC STUDY

General Statement.—The field work was conducted during the period from April, 1953, through August, 1953. Sixty-nine samples, 31 of which were selected for study, were collected from road cuts. The samples can be classified into six groups:

	Number of samples
1. White Limestone	9
2. Soil on White Limestone	9
3. Yellow Limestone	1
4. Soil on Yellow Limestone	1
5. Coastal Limestone	6
6. Soil on Coastal Limestone	5

The sources of these samples are shown on Figure 1.

Chemical Analyses.—The average chemical analyses, unweighted for area, of the samples from the White Limestone, Coastal Limestone, and their residual accumulations are shown in Table 1.

The R_2O_3 value in the White Limestone consists mainly of Al_2O_3 and Fe_2O_3. Other oxides with this general formula are rare and probably account for only a minor fraction of the R_2O_3 value. The ratio R_2O_3:TiO_2 in the

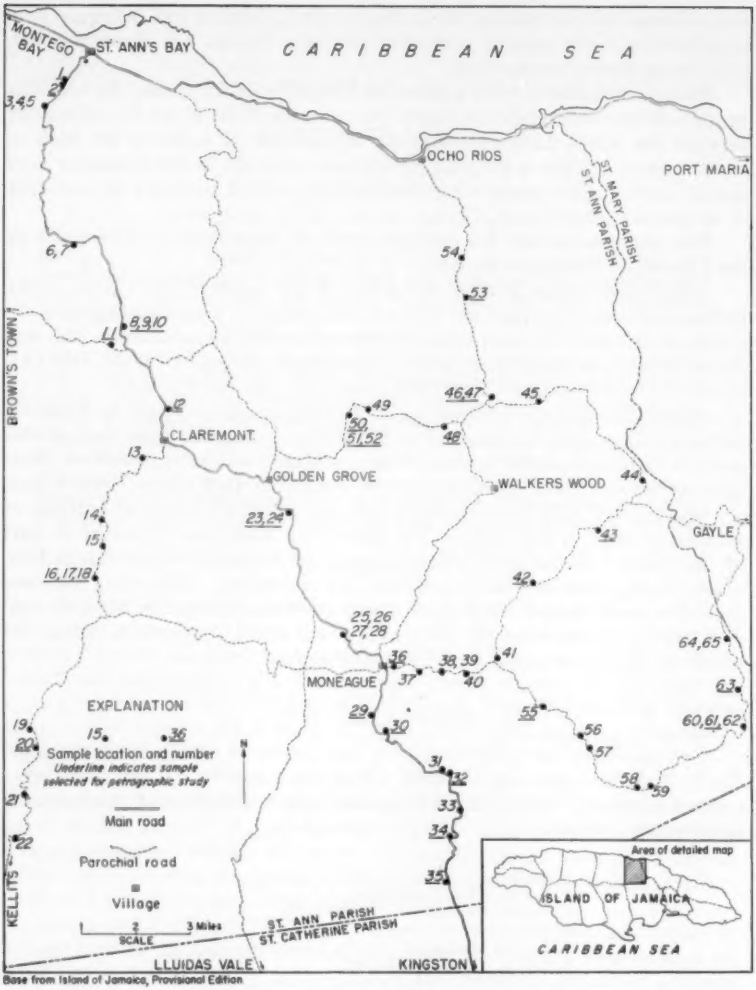

FIG. 1. Sample locations, St. Ann Parish, Jamaica, B. W. I.

White Limestone is 0.31:0.005 or 62. In the average bauxite containing 50% Al_2O_3 and 20% Fe_2O_3 this ratio is 70:2.25 or 31. Thus, it would appear that if the bauxite formed from the White Limestone the enrichment of TiO_2 in the residual accumulation was about two times greater than of alumina and iron.

Preparation of Samples.—One to two pounds of limestone were digested in HCl acid. The excess liquid was decanted, leaving the insoluble residue, which was then filtered and air-dried. This procedure was sufficient for the White Limestone, but the other limestones contained some clay-sized material that necessitated an additional step. The residues were returned to clean water, and a small amount of 0.5N sodium oxylate solution added as a dispersing agent. This solution was then agitated mechanically for five to ten minutes. Much, but not all, of the clay-sized material was removed in this manner.

The soil samples were treated in much the same manner except that the amount of material used was one-fourth to one-half pound.

Each residue was mounted in Canada balsam. The slides were studied under the microscope in transmitted light.

Table 2 lists the minerals identified in each sample. As an additional check the transparent minerals were examined in immersion oil, and their indices of refraction were roughly determined.

TABLE 1

AVERAGE CHEMICAL ANALYSES OF GEOLOGICAL UNITS

	LOI	SiO_2	NSI	Fe_2O_3	TiO_2	P_2O_5	MnO	CaO	Al_2O_3	R_2O_3	MgO
White Limestone	43.75	0.08	tr.	N.D.	0.005	0.034	0.004	55.76	N.D.	0.73[1]	0.20
Coastal Limestone	45.23	0.05	tr.	N.D.	0.004	0.057	0.003	54.32	N.D.	0.38	0.24
Clay	16.60	29.34	0.73	15.77	1.73	1.08	0.13	tr.	36.38	N.D.	0.06
Bauxite	25.86[2]	2.38	0.62	19.38	1.97	0.74	1.17[3]	tr.	50.32[2]	N.D.	N.D.

Explanation

LOI Loss on ignition
NSI Non-SiO_2 insolubles
tr. Trace
N.D. Not determined

Note

[1] Omitting sample 20, the average R_2O_3 value would be 0.31%.
[2] Omitting sample 51, the average LOI is 26.60%.
[3] Omitting sample 51 and sample 61, the MnO is 0.29% and the Al_2O_3 is 48.38%.

Summary of Results of Petrographic Studies.—The results of petrographic studies are shown in Table 2. The table shows that the minerals common to nearly all of the slides are zircon, magnetite, leucoxene, ilmenite, chalcedony, quartz, and glass. The insoluble residues of White Limestone and the Coastal Limestone contain the same mineral assemblage. So far as can be determined from the petrographic study of the insoluble residues either one of these formations could represent the source material of the bauxite.

Of particular significance is the occurrence of titanium minerals in the limestones. Their presence means that it is not necessary to postulate an igneous source for the bauxite. Any residual accumulation for the limestone would be expected to contain the titanium minerals since they are resistant to weathering.

MINERALOGRAPHIC STUDIES

General Statement.—Identification of the opaque minerals in transmitted light is difficult and such features as intergrowths, e.g., titaniferous magnetite,

cannot be observed. In order to obtain more detailed information on the opaque minerals some of the samples were selected for study in polished surface.

Insoluble residues from five samples, four of bauxite and one a composite of nine samples of White Limestone, were studied in reflected light. The Coastal formation and its soil could not be studied in reflected light because

TABLE 2

MINERALS IDENTIFIED IN TRANSMITTED LIGHT

Sample number	Rock type	Zircon	Magnetite	Leucoxene	Ilmenite	Chalcedony	Quartz	Rutile	Glass	Garnet	Tourmaline	Hematite	Tremolite	Chlorite	Unidentified mineral	Feldspar
18	W. Ls.	x	x	x	x	x	x									
20	W. Ls.	x	x	x		x	x			x						
23	W. Ls.	x	x	x	x	x	x		x							
24	W. Ls.	x	x	x	x	x	x		x	x	x					
29	W. Ls.	x	x	x	x	x	x		x		x	x	x			
32	W. Ls.	x	x	x	x	x	x		x			x				
34	W. Ls.	x	x	x	x	x	x		x	x			x		x	
50	W. Ls.		x	x	x	x	x								x	
55	W. Ls.		x	x		x	x					x				
63	Y. Ls.	x	x	x	x	x	x		x	x	x			x		
2	C. Ls.	x	x	x		x	x		x							
8	C. Ls.	x	x	x		x	x		x							
9	C. Ls.	x	x	x		x	x		x						x	
10	C. Ls.	x	x	x		x	x			x						
47	C. Ls.	x	x	x		x	x		x	x	x		x		x	
53	C. Ls.	x	x	x	x	x	x		x			x	x			
1	Clay		x	x	x	x	x		x	x	x				x	
11	Clay	x	x	x	x	x	x		x		x				x	
30	Clay	x	x	x	x	x	x	.	x							
36	Clay	x	x	x	x	x	x			x					x	
46	Clay	x	x	x	x	x	x	x	x		x					
61	Clay		x	x	x	x	x									
12	Baux.	x	x	x	x	x	x	x			x					
16	Baux.	x	x	x		x	x									
17	Baux.	x	x	x	x	x	x		x							
35	Baux.	x	x	x	x	x	x			x						x
42	Baux.	x	x	x	x	x	x									
43	Baux.	x	x	x	x	x	x			x	x					x
48	Baux.	x	x	x	x		x	x								
51	Baux.	x	x	x	x	x										
52	Baux.	x	x	x	x	x	x									

Identification is designated by x.

nearly all of their insoluble residues were used in the petrographic study. Each residue was briquetted in bakelite, polished, and examined under the microscope by reflected light. Modal analyses given below are based on counts of at least 500 grains in each surface.

Minerals Identified.—The following minerals were identified in the polished surfaces: ilmenite, silicates, rutile, leucoxene, limonite, hematite, magne-

TABLE 3

MINERALS IDENTIFIED IN REFLECTED LIGHT

Sample, number	Ilmenite	Silicates	Rutile and leucoxene	Limonite and hematite	Clay	Magnetite and titaniferous magnetite	Zircon	Titaniferous hematite	Covellite	Pyrite	Chalcopyrite	Composite grains	Unknown	Plucked
W. Ls.	14.9	7.1	1.3	2.2	nil	43.6	8.1	nil	8.4	1.3	1.3	2.0	6.2	3.7
12	16.9	24.7	6.3	2.7	nil	37.4	8.4	2.7	nil	nil	nil	nil	0.1	0.1
17	0.7	1.4	3.2	88.4	nil	4.3	0.4	0.1	nil	nil	nil	nil	nil	1.3
43	4.2	2.8	1.7	80.0	0.8	5.2	1.0	0.7	nil	0.1	nil	nil	0.7	3.7
52	6.7	1.6	2.8	68.9	nil	5.6	2.2	7.4	nil	nil	nil	nil	0.4	4.3

tite (titaniferous in part), clay, zircon, titaniferous hematite, covellite, pyrite, and chalcopyrite. Table 3 gives the percentages of the minerals in each surface.

Clay, hematite, and limonite are present in the surfaces because of incomplete treatment of the pulp of the samples. Silicates consist mainly of quartz as shown by the petrographic study, and these would float if the residues were placed in heavy liquids. These minerals are omitted to obtain a more accurate comparison of the heavy minerals, and the remaining constituents, i.e., ilmenite, rutile and leucoxene, magnetite, zircon, and titaniferous hematite, were recalculated to 100 percent. Table 4 lists these results.

Descriptions of Minerals

Ilmenite.—Ilmenite occurs in anhedral grains having a pinkish brown color. They are anisotropic and show sharp extinction. Some grains are partially altered to leucoxene.

Silicates.—A list of these is found in Table 2.

Rutile and Leucoxene.—Rutile is a very minor mineral in the surfaces. Only a few grains were seen. Leucoxene is more abundant than rutile and is highly variable in reflectivity and internal reflections; the latter feature masks anisotropism. Work in this laboratory indicates that leucoxene is commonly a micro-crystalline aggregate of rutile (11) or anatase, and is not

TABLE 4

HEAVY MINERALS IDENTIFIED IN REFLECTED LIGHT
(CALCULATED TO 100%)

Sample number	Ilmenite	Rutile and leucoxene	Magnetite and titaniferous magnetite	Zircon	Titaniferous hematite
W. Ls.	21.9	1.9	64.2	11.9	nil
12	23.6	8.3	52.3	11.7	3.8
17	8.1	36.8	49.5	4.7	1.1
43	32.8	13.3	40.6	7.8	5.5
52	27.2	11.3	22.6	8.9	30.0

a separate mineral species; this confirms earlier findings of Tyler and Marsden in 1938 (10).

Limonite and Hematite.—Limonite has a low reflectivity, is very soft, and shows yellow brown internal reflections. It is the most abundant mineral in three surfaces. Hematite is not common.

Magnetite.—Magnetite is the most abundant mineral in two surfaces. It is pinkish brown in color, isotropic, and occurs in anhedral, subhedral, and euhedral crystals. Many grains contains intergrowths of ilmenite that are aligned parallel to the octahedral parting of the magnetite.

Clay.—This mineral is a minor constituent of surface 43.

Titaniferous Hematite.—Titanium occurs as the mineral ilmenite intimately intergrown with hematite. This intergrowth is here designated as "titaniferous hematite." It is notably lacking in the White Limestone. The most common patterns that these intergrowths assume are: 1) thin lamellae oriented in the typical lattice type pattern of titaniferous magnetite; 2) an irregular pattern that looks like cross-bedding in sandstone.

Titaniferous hematite forms partly, perhaps entirely, by oxidation of the iron of titaniferous magnetite. When a grain of titaniferous magnetite is confined in the limestone, it has little chance of becoming altered. Once the titaniferous magnetite grain has been liberated from the limestone, however, oxidizing solutions can readily attack it and convert magnetite to martite. If the process is carried to completion magnetite is completely replaced by martite; ilmenite commonly is little affected and the result is a grain of hematite with ilmenite laths oriented as in titaniferous magnetite. This is one of the typical patterns noted above. Titaniferous hematite has clearly formed in this manner because all stages of alteration from completely unaltered titaniferous magnetite to the end product of titaniferous hematite are found in the bauxite.

Sulphides.—Covellite was found only in the limestone surface. It displays the usual distinctive optical properties.

Pyrite occurs in the limestone and in one bauxite sample. It is isotropic and has a cream yellow color in reflected light. The grains are small and without crystal faces.

Chalcopyrite occurs only in the limestone. It is slightly anisotropic, has a brassy yellow color, and occurs in anhedral grains.

The presence of sulphides in the limestone and their absence in the bauxite can be explained in two ways. First, sulphides are unstable in an oxidizing environment and are readily leached from any residual accumulation. Second, there are reasons to suspect that there may be some very minor mineralization of the limestone in this area.

Summary of Mineralographic Studies

Mineralographic study of the bauxite and White Limestone shows that the assemblage of opaque minerals is the same for both formations with the exceptions mentioned. The percentage of each mineral varies greatly from surface to surface. This is probably due to the lateral movement of the bauxite

involved in its accumulation. Because the bauxite occurs chiefly in the sink bottoms, some lateral movement of the material that formed on the hillsides must have taken place. This movement has been a local phenomenon, and the maximum migration is probably on the order of a few hundreds of feet. Because the constituents vary in grain size and in specific gravity, rough sorting of the minerals must occur during transportation. For this reason variations in the percentages of minerals in samples taken from road cuts are to be expected, particularly because the maximum thickness that could be sampled rarely exceeded four feet. The mineral assemblage, however, should be the same, and this was borne out by the petrographic and mineralographic studies.

The combined content of ilmenite, rutile and leucoxene shown in Table 4 varies from a minimum of 23.8 percent for the insoluble residue of the White Limestone to 46.1 percent for the insoluble residue of the bauxite. This variation can also be explained by the local concentration during transportation from hillsides. The increase of leucoxene in the bauxite as compared to the limestone is probably a consequence of the state of oxidation of the bauxite. Leucoxene is considered to be an alteration product of ilmenite. This alteration involves the oxidation and leaching of the iron in ilmenite (6, 11), a process that would be favored in the bauxite. Microscopic evidence supports this since some of the ilmenite grains in the bauxite are partially altered to leucoxene, whereas ilmenite in the White Limestone is fresh and generally unaltered.

The problem of titanium in bauxites derived from limestone has confronted geologists for some time and has often led to the assumption that the parent material for these bauxites is an igneous rock. The presence of titanium in the ore is one of the reasons that Goldich and Bergquist believe that the Hispaniola deposits were derived from an andesitic igneous rock.

The present study shows that the White Limestone formation of Jamaica contains titanium in the following minerals: ilmenite, rutile, leucoxene, and titaniferous magnetite. Oxidation of titaniferous magnetite of the limestone could readily yield the titaniferous hematite that is found in the bauxite. Because the limestone contains titanium minerals, any residual accumulation of the limestone must contain TiO_2. A separate layer of volcanic ash deposited on the White Limestone is not necessary to explain the presence of titanium.

The possibility that an igneous source may be the ultimate parent material of the bauxite is not precluded by this study. It is possible that volcanic ash became incorporated in the White Limestone during deposition and comprises the 0.49 percent impurities shown by chemical analysis. If this is true and if the White Limestone is the direct source of the bauxite, the correct theory of origin for these deposits may be one which combines the White Limestone and volcanic ash theories.

If the White Limestone formation represents the source of the material that formed the bauxite, large quantities of limestone must have been carried away in solution. The amount of limestone that would have to be dissolved can be calculated by using the content of Al_2O_3 in the limestone. Goldich and Bergquist state that the content of Al_2O_3 of the limestone in Hispaniola is

less than 0.1 percent (1, p. 53). Schmedeman says (8, p. 79) that the content of Al_2O_3 in the White Limestone formation of Jamaica varies from traces to 0.6 percent. The limestones used in this study were not analyzed for Al_2O_3 but instead a general R_2O_3 value was obtained. It is estimated that the St. Ann district contains 105,000,000 tons of bauxite (5, 8) in an area of about 63 square miles. If the bauxite were spread in a uniform blanket over the entire district, each square mile would be covered by 1,667,000 tons of ore. Assuming that the content of Al_2O_3 in the limestone is 0.075 percent, 667 tons of limestone would have to be dissolved to yield one ton of bauxite containing 50 percent Al_2O_3. By applying a factor of 20 cubic feet of limestone per ton, the required thickness of limestone to yield the bauxite is 800 feet. V. G. Hill (4) estimates that the thickness of limestone yielding the bauxite would be 750 feet. If the content of Al_2O_3 were higher in the limestone, as has been suggested by Schmedeman, the thickness of limestone would be decreased.

The White Limestone formation was elevated during Middle Miocene time (14, p. 4). If it represents the source of the bauxite, then the bauxite must have started to form at that time. It seems reasonable to expect that a thickness of limestone suggested above could have easily been dissolved since Middle Miocene in view of the high rainfall that must be present to form bauxite.

CONCLUSIONS

1. The White Limestone formation may well be the direct source of the bauxite. This conclusion is based on the following points:

a) The insoluble residues of the bauxite and White Limestone are mineralogically similar with the exception of titaniferous hematite. The titaniferous hematite in the bauxite could be readily derived, however, from titaniferous magnetite in the limestone by oxidation of the iron of magnetite.

Although the insoluble residues from the Coastal Limestone are mineralogically similar to those of the White Limestone, it is the opinion of geologists who have studied the Island in detail that the Coastal Limestone never covered the White Limestone. The Coastal Limestone, moreover, is in part derived from the White Limestone and would be expected to have a similar mineral assemblage in the insoluble residue.

b) The White Limestone contains a small but sufficient amount of impurities to yield the bauxite. A layer of limestone about 800 feet thick would contain enough impurities to produce the bauxite, assuming that the content of Al_2O_3 of the limestone is 0.075 percent. It is a reasonable inference that a thickness of limestone many times greater than that required to yield the bauxite could have been dissolved since Middle Miocene time.

2. The ultimate source of the impurities in the White Limestone may be a volcanic ash that settled into the basin of limestone accumulation.

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MADISON 6, WISCONSIN,
June 15, 1955

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SCIENTIFIC COMMUNICATIONS

SUMMARY OF "'ABOUT MINERALS—GEOCHEMICAL INDICATORS AND THEIR SIGNIFICANCE IN PROSPECTING FOR ORES OF RARE METALS IN PEGMATITES,' BY A. I. GINZBURG"[1]

A detailed study of the mineralogy of pegmatites reveals a series of *minerals-indicators,* which can be used to predict the presence of various rare metals in pegmatites. Because of the sporadic occurrence, prospecting for rare metals in pegmatites presents many difficulties. In addition, in many instances where pegmatites contain commercial ores of rare metals, the minerals of these metals are not exposed at the surface of outcrops.

The presence of rare metals in pegmatites depends largely on the degree of development of hydrothermal and pneumatolytic processes and is reflected in the chemical composition of accessory minerals. The following rules hold true in cases where some rare element reaches high concentration in pegmatites:

(a) The element of high concentration forms not only its own crystals but also is incorporated (isomorphic admixture) into the crystal lattices of other minerals in increased amounts.

(b) Minerals containing this element of high concentration are distinguished by wide range in temperatures of separation, and in some cases form at all stages of pegmatite formation.

(c) The normal sequence of separation of minerals is disturbed, and minerals that generally separate out during the latter stages of pegmatite formation can start separating much earlier.

Thus, accessory minerals are very good geochemical indicators, because the presence of increased amounts of rare metal in their crystal lattices is a good indication for the presence of ores of this rare metal.

DESCRIPTION OF GEOCHEMICAL INDICATORS IN PEGMATITES

The geochemical indicators that can be used successfully in prospecting for ores of rare metals in pegmatites are as follows:

1. Tourmaline.—One of the minerals that reflects the type of mineral-forming processes that occurred in pegmatites is tourmaline. The dark blue tourmaline (indigolite) and green tourmaline ("verdelite") are widespread in cases of intensive albitization, which is genetically related to the tantalum-niobium and tin ores, whereas the pegmatites devoid of replacement processes

[1] Ginzburg, A. I., 1954, About minerals—geochemical indicators and their significance in prospecting for ores of rare metals in pegmatites: Doklady Akademii Nauk SSSR, vol. XCVIII, no. 2, p. 233–235.

generally contain only black tourmaline (schorl). The pink and red varieties of tourmaline (rubellite) and polychrome tourmaline appear in cases of extensive lepidolitization, which is associated with the specific ore minerals containing cesium (Cs), lithium (Li), rubidium (Rb), and tantalum (Ta).

The color of tourmaline is due to the variable content of FeO, MnO, and presence of small amounts of Fe_2O_3 and Mn_2O_3. In the process of pegmatite formation there is a gradual decrease in FeO and increase in MnO contents up to a certain limit, which is reached during the albitization stage. A rapid decrease in the amount of MnO occurs towards the end of the process and MnO is partly oxidized to Mn_2O_3. Thus, there is a gradual changing of color from black to blue, green, colorless, and finally pink.

2. Secondary Phosphates of Iron and Manganese.—As a result of oxidation of the triphylite-lithiophyllite group of minerals, considerable amounts of black, dark-brown, and dark-violet secondary phosphates of iron and manganese ("heterosite," purpurite, and sicklerite) form on the surface of pegmatite bodies.

The triphylite-lithiophyllite group of minerals is in turn associated with beryl, columbite, or spodumene, and in many instances forms large (up to 0.5 m and larger) irregular bodies and nodules. Around such bodies all minerals of pegmatites are pierced with black films of oxides and hydroxides of manganese. Consequently, the appearance of black phosphates is a good indicator for the presence of beryl, columbite, and spodumene.

3. Cs:Rb Ratio.—Lepidolites always contain certain amounts of Cs and Rb, which replace K in their crystal lattices, and the Cs:Rb ratio generally varies from 1:10 to 1:20. However, the Cs:Rb ratio of lepidolites from pegmatites rich in pollucite approaches 1:1 (Ginzburg, 1953, in Ginzburg, 1954). Therefore, from the amount of Cs present in lepidolites one can evaluate the possibility of finding pollucite ores.

4. Amount of Sn in Micas.—As shown by S. A. Borovik, 1937 (in Ginzburg, 1954), small amounts of Sn are always present in micas, partly as very fine grains of cassiterite and in part as an isomorphic admixture in the crystal lattices. The micas from pegmatites rich in cassiterite contain up to 0.4 to 0.5 percent SnO_2, whereas in pegmatites devoid of Sn the amount of Sn present in micas is negligible.

5. Nb:Ta Ratio in Cassiterite.—A. M. Boldyreva, 1941, and I. F. Grigor'ev and E. I. Dolomanova, 1951 (in Ginzburg, 1954) showed that Nb and Ta are two important typomorphic admixtures of cassiterites from pegmatites, and are present in the form of very fine-grained columbite-tantalite group of minerals. Generally Nb > Ta in cassiterite, but in areas rich in Ta the Ta > Nb. Therefore, the Nb:Ta ratio is a useful tool for predicting the tantalum content of pegmatites.

6. Spessartite and Orthite.—Spessartites from pegmatite dikes may contain increased concentrations of yttrium (Y), and show characteristic heterovalent isomorphism—YAl replacing MnSi. However, the early spessartite from pegmatites that contain xenotime, fergusonite, thalenite, gadolinite, tengerite, yttrialite, and other yttrium minerals is most highly enriched in Y. Thus, spessartite can be considered as a *mineral-indicator* for yttrium.

Orthite (allanite), which concentrates scandium (Sc), plays a similar role for Sc as spessartite does for Y.

CONCLUSIONS

The geochemical indicators that are of great value in prospecting for rare metals in pegmatites are as follows:

1. Tourmaline—The color of tourmaline reflects the type of mineral-forming processes that occurred during the formation of pegmatites.
2. The appearance of black phosphates of iron and manganese is a good indicator for the presence of beryl, columbite, and spodumene.
3. The Nb:Ta ratio in cassiterites is a useful tool for predicting the tantalum content of pegmatites.
4. Lepidolite is a geochemical indicator for Cs, muscovite for Sn, early spessartite for Y, and orthite for Sc.

It is hoped that further study will augment the above list.

ACKNOWLEDGMENT

Review of manuscript by John R. Currey, Chief of Petroleum and Chemicals Laboratory, Wright-Patterson Air Force Base, Ohio, is greatly appreciated by the reviewer.

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June 13, 1955

DISCUSSION

COMMENTS ON URANIUM ORE CONTROLS OF THE HAPPY JACK DEPOSIT, WHITE CANYON, SAN JUAN COUNTY, UTAH

Sir: In his paper "Uranium Ore Controls of the Happy Jack Deposit, White Canyon, San Juan County, Utah" (ECON. GEOL., vol. 50, p. 163, 1955), Mr. Leo J. Miller states that "chalcopyrite and bornite, where found together, are always in a grating pattern, bornite being the included mineral. This is apparently an exsolution texture. . . ." Since G. M. Schwartz was able to produce such textures in chalcopyrite-bornite ore at a minimum temperature of 475° C in dry specimens, Miller concludes that the Happy Jack ores must have been at elevated temperatures though not necessarily as high as that. In this connection a significant article by James C. Ray [1] may be recalled. Ray experimentally produced textures like these in bornite in aqueous solutions at temperatures of 90°–100° C (his Fig. 7, p. 445) in 8 days. Maynard Stephens and the writer made similar unpublished experiments at about 125° C and obtained results in 24 hours which seems to indicate that these reactions could occur at still lower temperatures given sufficient time. Any of the sulfides and combinations of them found in the Happy Jack ores probably can form at temperatures of ordinary sedimentary environments given the proper proportions of Cu and Fe ions in the solutions. That uraninite can form at room temperature has been demonstrated by the writer.[2]

There is nothing that indicates hydrothermal alteration as already pointed out by Miller. It is true that the amount of copper sulfides is larger than generally found in sedimentary uranium deposits, but it was far too small to have made the mining of copper profitable even during the world wars. Some copper deposits in the Permian Red Beds are of comparable size.

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June 18, 1955

THE ELIZABETH COPPER MINE, VERMONT

Sir: A recent paper on the Elizabeth Mine, by McKinstry and Mikkola (ECON. GEOL., vol. 49, p. 1–30, 1954), reports a mineral tentatively identified as valleriite. Further work on McKinstry and Mikkola's specimens has confirmed their provisional identification. N. W. Burger (1) has previously

[1] Synthetic sulphide replacement of ore minerals: ECON. GEOL., vol. 25, p. 433–451, 1930.

[2] U. S. Atomic Energy Commission, Annual Report, 1954, RME-3094 p. 29.

identified valleriite from the Elizabeth, Ely, and Pike Hill Mines, Vermont.

Since considerable genetic interest is attached to the phases appearing in assemblages of copper-iron-sulfur minerals, other workers may find the criteria used to determine valleriite useful.

Valleriite appears to have hardness of about B, and a high reflectivity. The most distinctive feature is a strong pleochroism, from pale yellow to deep creamy brown. Anisotropism is very strong. In a complete revolution of the stage, grains show four extinction positions, between which are two positions showing a bright cream-yellow color and two positions showing a bluish-gray color. In some orientations of the mineral the bluish-gray positions are very dark. In a specimen from Kaveltorp, Sweden, all four positions of maximum brightness show cream color, although one pair has a distinct bluish tinge.

In some positions, the color of valleriite may lead to confusion with pyrrhotite, and it is possible that valleriite has been overlooked in some chalcopyrite-pyrrhotite ores for this reason.

Valleriite has a layer structure (2) with a basal spacing of 11.46 Å. This structure leads to a very distinctive X-ray power diffraction pattern. Material from the Elizabeth Mine was photographed in Fe radiation using a Mn filter. Because of the very small size of the valleriite grains, the only samples obtained were highly impure, containing both chalcopyrite and pyrrhotite. The basal reflections of the valleriite are so strong, however, that even such an impure sample yields a photograph satisfactory for identification.

The d spacings for the strongest reflections are given below.

d (A)	Index
11.46	001
5.74	002
3.82	003
3.27	030
2.86	004
2.37	222
2.28	005
1.90	006

The d spacings are for material from Kaveltorp, Sweden, as we had relatively pure material from that locality, which yielded very clear photographs. The d spacings check with those calculated from data presented by Hiller (1939) on similar material from Kaveltorp. The indices are after Hiller, calculated for an orthorhombic unit cell.

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Laboratory of Mining Geology,
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April 2, 1954

B. J. Skinner and D. J. Milton

REVIEWS

Spezielle Mineralogie auf geochemischer Grundlage. By F. MACHATSCHKI. Pp. 378; figs. 229. Springer-Verlag. Wien, 1953. Price, $8.60.

This book could be called a "Petrogenetic and Geochemical mineralogy." Most of the minerals contained in Winchell's new "Elements of Optical Mineralogy" are described with regard to crystal structure, forms, and composition, occurrence, frequency, and association. The arrangement is not according to the conventional chemical subdivision. Machatschki makes four subdivisions: (1) primary minerals, (2) weathering and sedimentary minerals, (3) metamorphic minerals and rocks, and (4) metallic ore minerals. The German is very clear and, altogether, this is an excellent reference book for the American petrologist and mineralogist who wants to dig into German mineralogic and petrologic literature.

G. C. AMSTUTZ

PETROLOGIST,
CERRO DE PASCO CORP.,
CERRO DE PASCO, PERU,
July 26, 1955

Regional Tectonics of the Colorado Plateau and Relationship to the Origin and Distribution of Uranium. By V. C. Kelley. Pp. 120; figs. 17; pls. 8. University of New Mexico. Pub. in geology, No. 5, 1955. Price, $2.00.

This interesting bulletin was prepared in cooperation with the U. S. Atomic Eneregy Commission, Division of Raw Materials. It also carries a tectonic map of the Colorado Plateau on a scale of approximately 1:1,000,000 showing the uranium deposits.

The bulletin deals with Geography, Tectonics, Geologic History, and Tectonic Influence on Distribution and Genesis of Ore. Under Tectonics there is discussed major primary rock masses, the various structural elements, lineaments and regional mechanics of deformation. The geologic history deals mainly with the geologic development of the structural features.

Under the tectonic influence on the distribution and genesis of ore there is considered the distribution, theories of origin, sources of ore-bearing sediments, paleohydrology, and hydrothermal activity. The conclusion is reached that there is no direct relationship between large tectonic features, such as uplifts, anticlines or basins, and any concentration of uranium deposits on the Plateau. The author recalls the age determinations that show the uranium deposits to be much later than the host rocks and, therefore, epigenetic. He supports the hypothesis that hydrothermal emanations have been added to the meteoric ground water systems, contaminating it, and that from these contaminated meteoric waters the uranium minerals were deposited. Consequently, he stresses the paleohydrodynamics of ground water in the Plateau as the chief factor in giving rise to the distribution of the uranium deposits.

BOOKS RECEIVED

KURT SERVOS

U. S. Geological Survey. Washington, D. C., 1950–1955.

Prof. Paper 246. Geology of the Deep River Coal Field, North Carolina. J. A. REINEMUND. Pp. v, 9–159; figs. 39; pls. 8; tbls. 19. Price, $4.25. *Deep River coal field contains the only commercially important beds of coal in North Carolina. Basic intrusions metamorphosed the coal to semianthracite, anthracite, and coke. Coal mining has been intermittent since before the Revolutionary War; production totals more than one million tons. Total reserve of unmined coal is estimated at more than 110 million tons, only half being recoverable. Geologic map, 1:30,000; structure map, 1:96,000.*

Prof. Paper 259. Geology of the Bedford Shale and Berea Sandstone in the Appalachian Basin. J. F. PEPPER, W. DE WITT, JR. and D. F. DEMAREST. Pp. vi, 111; figs. 61; pls. 14. Price, $4.25. *The comprehensive study of Bedford shale and Berea sandstone (Lower Mississippian) in Ohio and adjacent states covers stratigraphy, sedimentation and paleogeography.*

Prof. Paper 264-I. A Biofacies of Woodbine Age in Southeastern Gulf Coast Region. E. R. APPLIN. Pp. iii, 187–197; fig. 1; pl. 1; tbl. 1. Price, 45 cts.

Prof. Paper 264-J. Fossil Birds From Manix Lake, California. HILDEGARDE HOWARD. Pp. iii, 199–205; fig. 1; pl. 1. Price, 40 cts.

Bull. 974-B. Volcanic Activity in the Aleutian Arc. R. R. COATS. Pp. 35–49; fig. 1; pl. 1; tbls. 3. Price, 40 cts. *Thirty-six of at least 76 major volcanoes have been active since 1760.*

Bul. 981-D. Geophysical Abstracts 147, October–December, 1951. M. C. RABBITT and S. T. VESSELOWSKY. Pp. 175–281. Price, 30 cts.

Bull. 1000-B. Geochemical Prospecting Investigations in the Nyeba Lead-Zinc District, Nigeria. H. E. HAWKES. Pp. iv, 51–103; figs. 13; tbls. 8. Price, 25 cts. *Systematic sampling and trace analysis of soils and other weathering products may constitute an important method of exploration in a tropical environment.*

Bull. 1008. Geology and Mineral Deposits of the James River-Roanoke River Manganese District, Virginia. G. H. ESPENSHADE. Pp. vii, 155; figs. 14; pls. 12; tbls. 4. *Mn is associated, to a maximum depth of more than 300 ft, with beds of the Mount Athos formation. Concentration is due to leaching; most of the deposits crop out on an upland surface above present streams. Production has been sporadic, totalling 52,779 long tons of washed ore. Average grade is 43.3% Mn and other economic minerals include iron, barite, copper, and lime. Two geologic maps, 1:62,500.*

Bull. 1009-E. Stratigraphy of the Morrison and Related Formations, Colorado Plateau Region. L. C. CRAIG and others. Pp. iv, 126–168; figs. 19–31; tbl. 1. Price, 20 cts. *Shapes of carnotite deposits are possibly influenced by primary sedimentary structures but the ore deposits show little control by sedimentary structures (ore cuts across bedding in many places). Stratigraphic studies furnished little evidence for determining the most probable original source of ore.*

Bull. 1015-G. Zinc-Lead-Copper Resources and General Geology of the Upper Mississippi Valley District. A. V. HEYL, E. J. LYONS, A. F. AGNEW, and C. H. BEHRE, JR. Pp. 227–245; figs. 2; pls. 2; tbl. 1. Price, 70 cts. *Ores are chiefly in the Galena, Decorah and Platteville formations (Middle Ordovician). Ore is*

in the form of veins, replacements and impregnations; it occurs along shears and faults.

Bull. 1024-A. Radioactivity Investigations in the Cache Creek Area, Yentna District, Alaska, 1945. G. C. ROBINSON, H. WEDOW, JR., and J. B. LYONS. Pp. iv, 23; figs. 4; pls. 6; tbls. 7. Price, 65 cts. *Radioactivity is due chiefly to U and Th in zircon, monazite and uranothorianite.*

Bull. 1027-A. Physical Stratigraphy of the Phosphoria Formation in Part of Southwestern Montana. E. R. CRESSMAN. Pp. iv, 31; figs. 12; pls. 5; tbls. 2. Price, 55 cts.

Bull. 1030-A. Search for Uranium in the United States. V. E. MCKELVEY. Pp. iv, 64; figs. 5. Price, 25 cts. *The published information is collated into a readable review.*

Bull. 1033-A. Geophysical Abstracts 160, January–March, 1955. M. C. RABBITT, D. B. VITALIANO, S. T. VESSELOWSKY, and others. Pp. 1–73. Price, 25 cts.

Water-Sup. Pap. 1259. Geology and Ground-Water Resources of the Fort Berthold Indiana Reservation, North Dakota. R. J. DINGHAM and E. D. GORDON. Pp. vi, 114; figs. 15; pls. 2; tbls. 1. *Lignite, sand and gravel are the principal mineral resources; some lignite mines will be flooded by water impounded due to Garrison Dam. Areal geologic map, 1:96,000.*

U. S. Department of the Interior, Bureau of Mines. Washington, 1955.

Spec. Supplement 44, Vol. 40, no. 1. Pp. 9. *Résumé of the mining laws in Venezuela.*

U. S. Atomic Energy Commission, Grand Junction Operations Office. Grand Junction, Colorado, 1955.

RME-74. Mineralogy and Paragenesis of the Uranium Ore of Mi Vida Mine, San Juan County, Utah. E. B. GROSS. Pp. 75; figs. 43; tbls. 8. *Mineralization consists of uraninite, coffinite, and various vanadium minerals in lower Chinle sandstone. A few sulphides appeared late in the mineral sequence. Replacement ore textures are common in the sedimentary mineralization.*

Arizona Bureau of Mines. Tucson, 1955.

Bull. 165. One Hundred Arizona Minerals. R. T. MOORE. Pp. 35. Price, 30 cts.

California Div. of Mines. San Francisco, 1954.

Spec. Rept. 40. Geology and Mineral Deposits of the Calaveritas Quadrangle, Calaveras County, California. Pp. 23; figs. 7; pls. 2. Price, $1.75. *Gold has been surpassed in economic importance by limestone. Dormant mineral potential includes asbestos, talc, copper, chromite, pozzolanic materials, and iron. Geologic map, 1:24,000.*

Illinois Geological Survey. Urbana, 1955.

Rept. of Invest. 181. Subsurface Geology and Coal Resources of the Pennsylvanian System in Jasper County, Illinois. F. E. WILLIAMS and M. B. ROLLEY, Pp. 14; figs. 6; pls. 3; tbl. 1. *Coal reserve estimates total more than 3.2 billion tons for two of the four coal beds.*

Rept. of Invest. 182. Structure of the Shoal Creek Limestone and Herrin (No. 6) Coal in Wayne County, Illinois. E. P. DU BOIS and RAYMOND SIEVER. Pp. 7; figs. 2; pls. 2. *The area lies near the deepest part of the Illinois Basin and the present structural configuration resulted from movement that took place in Carboniferous time.*

Rept. of Invest. 183. Subsurface Geology and Coal Resources of the Pennsylvanian System in Wabash County, Illinois. G. H. CADY, M. B. ROLLEY, ADABELL KARSTROM, M. A. PARKER, and M. E. HOPKINS. Pp. 24; figs. 7; pls. 4; tbls. 4. *The county has coal reserves estimated at 1.2 billion tons.*

Rept. of Invest. 184. Illinois Building Stones. J. E. LAMAR and H. B. WILLMAN. Pp. 24; figs. 12. *White, gray, buff, and brown building stones are suitable for a great variety of purposes in an expansible industry.*

Circ. 195. Faults and other Structures in Southern Illinois. H. B. STONEHOUSE and G. M. WILSON. Pp. 4. *Map with a scale of 1:181,028 contains all known faults, folds, and igneous intrusions in an area bearing coal, oil and gas, fluorspar, and other mineral resources.*

Circ. 196. Mineral Resource Research and Activities of the State Geological Survey, 1953–1954. M. M. LEIGHTON. Pp. 56; figs. 21. *The value of minerals produced in Illinois during 1953 was more than $500 million.*

Circ. 197. Effect of Diluents on the Plastic Properties of Coal as Measured by the Gieseler Plastometer. O. W. REES and E. D. PIERRON. Pp. 16; figs. 9; tbls. 5.

Bull. 65. Geology of the Chicago Region, Part II—The Pleistocene. J H. BRETZ. Pp. 132; figs. 61; tbl. 1; 20 geologic quadrangle maps.

Indiana State Geological Survey. Bloomington, 1955.

Directory No. 3. Directory of Producers and Consumers of Clay and Shale in Indiana. H. H. MURRAY. Pp. 42; figs. 4; pl. 1. Price, 25 cts.

Kansas State Geological Survey. Lawrence, 1955.

Bull. 111. Petrography of Upper Permian Rocks in South-Central Kansas. ADA SWINEFORD. Pp. 179; figs. 13; pls. 24; tbls. 8. *Commercial use of the deposits is currently restricted to salt, gypsum, and dolomite but some of the shale is potentially useful for ceramic purposes.*

Bull. 114, Part 3. Magnetic Anomalies in Wilson and Woodson Counties, Kansas. W. W. HAMBLETON and D. F. MERRIAM. Pp. 113–128; figs. 3; pls. 3.

Bull. 114, Part 4. Stone Corral Structure as an Indicator of Pennsylvanian Structure in Central and Western Kansas. D. F. MERRIAM. Pp. 133–152; figs. 11. *Structure contours on a formation of Permian age reflect Pennsylvanian structure in nine out of ten oil fields.*

Oil and Gas Investigation No. 13. Tectonic History of the Cambridge Arch in Kansas. D. F. MERRIAM and W. R. ATKINSON. Pp. 28; figs. 14. *Drilling for oil has yielded much new information about this little-known major structural feature. Production from the Arbuckle group is seemingly independent of structure; the traps are probably stratigraphic.*

North Dakota Geological Survey. Grand Forks, 1955.

Bull. 28. Contributions to the Geology of North Dakota. Students and Staff, Department of Geology, University of North Dakota. Pp. 83–156. *The nine diverse papers include two in economic geology.*

Report of Investigation 18. Geology of the Elkhorn Ranch Area, Billings and Golden Valley Counties, North Dakota. B. M. HANSON. *Geological and structural map, 1:125,000.*

Ohio Department of Natural Resources. Columbus, 1954.

Report of Investigation No. 24. 1954 Oil and Gas Developments in Ohio. R. L. ALKIRE. Pp. vi, 58; chart 1; figs. 8; tbls. 13. *Nearly 1200 new wells were complete in 1954; 788 were successful.*

Annual Report, 1953–1954. A. W. MARION and others. Pp. 271.

Oregon Department of Geology and Mineral Industries. Portland, 1955.

G.M.I. Short Paper No. 18. Radioactive Minerals the Prospector Should Know. D. J. WHITE. Pp. 21; tbls. 4. Price, 30 cts.

Pennsylvania Geological Survey. Harrisburg, 1955.

Inf. Circ. 5. Relation of Stratigraphy and Structure to Uranium Occurrences near Mauch Chunk, Pennsylvania. J. L. DYSON. Pp. 124–134; figs. 2. *Mineralization is due to sedimentary control.*

Inf. Circ. 6. The Mineral Industry of Pennsylvania in 1952. R. H. MOTE and ALVIN KAUFMAN. Pp. 32; pls. 18. *A summary by mineral commodities precedes a short review for each county.*

Progress Rept. 145. Preliminary Report, Occurrence of Rock Salt in Pennsylvania. C. R. FETTKE. *Greatest total thickness is 660 feet.*

Progress Rept. 146. Ground Water Resources of the Lansdale Area, Pennsylvania. D. R. RIMA. Pp. 24; figs. 4; tbl. 1. *Ground water occurs in Brunswick shale (Upper Triassic) near the surface.*

Progress Rept. 148. Summary, Secondary Recovery Operations in Pennsylvania to January 1, 1954. W. S. LYTLE. Pp. 23; figs. 9; tbls. 3. *By January 1954 Pennsylvania produced almost 1.2 billion bbl of crude oil since the discovery of the Drake well in 1859.*

Texas Bureau of Economic Geology, Austin. 1955.

Rept. of Invest. 24. The Faunas of the Riley Formation in Central Texas. A. R. PALMER. Pp. 709–786; figs. 6; pls. 16; tbls. 3. *Previously undescribed fossils are two families, four genera and 16 species of trilobites and three genera and five species of brachiopods.*

Rept. of Invest. 25. Geology of Cathedral Mountain Quadrangle, Brewster, County, Texas. W. N. MCANULTY. Pp. 531–578; figs. 3; pls. 3.

Virginia Geological Survey. Charlottesville, 1955.

Circ. 3. Records of Selected Wells on the Eastern Shore Peninsula, Virginia. ALLEN SINNOTT and G. C. TIBBITTS, JR. Pp. 39; figs. 3; tbls. 6.

Virginia Geological Survey. Charlottesville, 1954.

Bull. 71. Geology and Oil Resources of the Rose Hill District—the Fenster Area of the Cumberland Overthrust Block—Lee County, Virginia. R. L. MILLER and J. O. FULLER. Pp. xxiii, 383; figs. 17; pls. 50; tbls. 17. *Oil production in the Rose Hill field, from rocks of Ordovician age, is a few hundred bbl/day. Beds of low-grade hematitic iron ore (Silurian) no longer have economic importance. Geologic maps, 1:12,000 and 1:24,000.*

Reprint Series No. 17. Geology of Bergton Gas Field, Rockingham County, Virginia. R. S. YOUNG and W. T. HARNSBERGER. Pp. 317–328; figs. 3. *This small potential field in the folded Appalachians has a carbon ratio in excess of 80.*

Geological Survey of Wyoming. Laramie, 1954.

Rept. of Invest. 4. Radioactive Fossil Bones in Teton County, Wyoming. K. G. SMITH and D. A. BRADLEY. Pp. 12; figs. 7; tbl. 1.

Geol. Soc. of America. 1955.

Memoir 63. Paleozoic and Mesozoic Rocks of Gros Ventre, Teton, Hoback, and Snake River Ranges, Wyoming. H. R. WANLESS, R. L. BELKNAP, and HELEN FOSTER. Pp. vii, 90; figs. 6; pls. 23; tbls. 5.

Ontario Department of Mines. Toronto, 1955.

Sixty-Third Annual Report, Vol. LXIII, Part 3, 1954. Natural Gas and Petroleum in 1953 and Logs of Wells for 1953. R. B. HARKNESS. Pp. iv, 138; figs. 14; tbls. 18.

Sixty-Third Annual Report, Vol. LXIII, Part 5, 1954. Geology of the Emo Area. G. L. FLETCHER and T. N. IRVINE. Pp. iv, 36. *Ni and Cu sulphides occur as local disseminations without structural control in Dobie basic intrusive (norite phase). Principal ore minerals are pyrrhotite, pyrite, pentlandite, chalcopyrite, with small amounts of violarite, sphalerite, magnetite. An iron formation has too much overburden to constitute a good ore at the present time. Geologic map, 1:63,360.*

Manitoba Department of Mines and Natural Resources. Winnipeg, 1955.

Publication 54-1. Geology and Mineral Deposits of the Bird Lake Area. Pp. 44. *Mineral deposits include base metal (Ni and Cu, or Cu alone) sulphides; chromite; and pegmatites with lithium minerals, beryl, and cassiterite. Geologic map, 1:12,000.*

XIX Congrès Géologique International, Faculté des Sciences. Alger, Algérie, 1953–1954.

Comptes Rendus de la Dix-Neuvième Session, Alger, 1952.

Fasc. VI. La Genèse Des Roches Filoniennes (A l'exclusion des filons métallifères). P. PERRIN and M. E. ROUBAULT. Pp. 201–216; pls. 2. *The decision in the controversy between an injection or a replacement origin of aplite and of pegmatite dikes here goes to replacement.*

Bureau de Recherches Minières de l'Algérie. Alger, 1955.

Bulletin Scientifique et Economique du B. R. M. A. Pp. 7–63; figs. 7; pls. 3. *The two papers show that in the Bou Kaïs massif copper mineralization (chalcocite) is contemporaneous with alteration, ore is disseminated and presumably hydrothermal, and a gossan is lacking; and that the iron of the Gara Djebilet district, at the base of the upper Lower Devonian (Emsien), is oolitic sedimentary ore with an average grade of ca. 56% and proved reserves of more than 2000 million tons. Geologic maps, 1:50,000 and 1:100,000, respectively.*

Australia Bureau of Mineral Resources, Geology and Geophysics. Melbourne, 1954.

Rept. 15. Progress Report on the Stratigraphy and Structure of the Carnarvon Basin, Western Australia. M. A. CONDON. Pp. iv, 163; figs. 3; pls. 3; tbls. 2. *Only a few nonmetallic minerals, in unproved quantity, comprise the economic resources.*

Bureau of Mineral Resources, Geology and Geophysics. Melbourne, 1955.

The Australian Mineral Industry. Vol. 7, no. 3. Pp. iv, 49–74; iv, 18. Price, 3/–. *The quarterly average production of metals for 1954 was greater than that for 1953 for all principal metals except tungsten; tin and copper recorded the largest increases.*

Brazil Div. of Geol. and Mineralogy. Rio de Janeiro, 1954.

Relatório Anual do Diretor, 1953. Pp. 93.

Bull. 79. Uma Chaminé Vulcânica no Distrito Federal. A. R. LAMEGO. Pp. 12.

Bull. 84. Nota Sôbre o Distrito Alcalino de Jacupiranga, Estado de São Paulo. G. C. MELCHER. Pp. 20; fig. 1. *Leaching of an intrusive carbonate core has concentrated seven million tons of phosphate ore averaging 23 percent P_2O_5 in a district of alkaline and ultramafic rocks.*

Bull. 86. Botucatu, um Deserto Triássico da América do Sul. F. F. M. DE ALMEIDA. Pp. 21.

Bull. 90. Geologia Para Túneis e Geologia Para Barragens. OCTÁVIO BARBOSA. Pp. 31.

Bull. 150. Geologia do Centro-Leste Mato-Grossense. F. F. M. DE ALMEIDA. Pp. 92; figs. 10; pls. 34.

Geological Survey Department, British Territories in Borneo. Kuching, Sarawak, 1954–55.

Mem. 1. The Geology and Mineral Resources of the Strap and Sadong Valleys, West Sarawak, including the Klingkang Range Coal. N. S. HAILE. Pp. xii, 150; figs. 17; pls. 36; tbls. 17. Price, M$6.00. *Coal, of Eocene (?) age, is high-grade bituminous and has good coking qualities. Reserves are estimated at almost five million tons. Geologic map, 1:125,000.*

Mem. 2. The Coal Deposits and a Summary of the Geology of the Silimpopon Area, Tawau District, Colony of North Borneo. P. COLLENETTE. Pp. vi, 74; figs. 5; pls. 12; tbls. 20. Price, M$6.00. *Coal is high rank subbituminous, only in one seam. Geologic map, 1:125,000.*

Annual Report for 1954. F. W. ROE. Pp. v, 188; figs. 25; pls. 50; tbls. 22. Price, M$3.00. *More than 36 million bbl of oil represent the chief mineral export for 1954. Development of offshore oil is in the initial stages. Very minor resources include building stone, gold, phosphate, chromite, coal, antimony, mercury, copper, bauxite, and manganese.*

British Guiana. Geological Survey Department. Georgetown, 1954.

Report on the Geological Survey Department of British Guiana for the Year 1953. Pp. 111; figs. 41. Price, $2.00. *During 1953 more than two million tons of bauxite and 17,277.68 ounces of gold were produced.*

Geological Survey of the British Solomon Islands. Honiara, 1955.

Mem. 1. Geology, Mineral Deposits and Prospects of Mining Development in the British Solomon Island Protectorate. J. C. GROVER. Pp. 108; figs. 55; pls. 41. Price, 1/10/0. *This geologically little-known archipelago has currently no mining activity but Grover's comprehensive treatment indicates vast riches of mineral potential that warrant extensive development. Observed economic minerals include gold, silver, copper, chromite, platinum, barite, asbestos, talc, manganese, sulphur, gypsum, and alum.*

Mining, Geological and Metallurgical Institute of India. Calcutta, 1954.

Vol. 49, December, 1952. Recommendations of the Implementation Committee and the Proceedings of the Symposium on Training of Personnel for the Mineral Industry. Pp. 335. Price, Rs 15/. *Proceedings of a symposium on personnel training constitutes entire volume.*

Rajputana University. Udaipur, 1954.

Mem. 3. Pegmatites, Our Museums of Minerals. N. L. SHARMA. Pp. 41; pls. 5.

Geological Survey of Japan. Hisamoto-cho, Kawasaki-shi, 1954.

Rept. No. 101. Explanatory Text of the Geological Map of Japan. KIYOO KAWADA and ATUSHI OZAWA. *Copper ore (1.7% Cu) is associated with post-Paleozoic rhyolite and is the source of 3,000 metric tons of metal annually; Zn and Pb are by-products. Paleozoic sediments contain rhodochrosite (35–40%) which is mined. Geologic map, 1:50,000. Text in Japanese; résumé in English.*

Northern Rhodesia Geological Survey. Lusaka, 1955.

Records of the Geological Survey for 1953. Pp. 24. Price, 2/6. *Several brief preliminary notes dealing with regional and economic geology and with other problems. Mineral deposits, some of questionable commercial value, include: asbestos, barite, betafite, beryl, graphite, gold, phosphate, ilmenite, limestone, mica, columbite, and apatite.*

Annual Report for the Year 1954. Pp. 10. Price 2s.

The Lead-Zinc-Vanadium Deposits at Broken Hill, Northern Rhodesia. J. H. TAYLOR. Pp. 335–365; figs. 9; pls. 2. *Deposits occur in massive dolomites of Katanga System. Orebodies consist of massive sulphide cores (averaging 34.4% Zn and 24.8% Pb) surrounded by a sheath of oxidized ore (22.0% Zn and 12.7% Pb).*

Consejo Superior de Investigaciones Cientificas. Barcelona, 1954.

Publications del Departamento de Cristalografia y Mineralogia. Vol, 1, no. 3. Pp. 111–175. *Eight diverse papers on crystallography.*

Tanganyika Geological Survey Department. Dar es Salaam, 1955.

Rept. No. 1. The Tunduru-Ruvuma Area of the Southern Province, A Reconnaissance of the Geology, Soils, Vegetation and Hydro-electric Potential. D. R. GRANTHAM. Pp. 14. Price, 3/–. *Alluvial gold occurs in the Muhuwesi River. Geologic map, 1:250,000.*

Annual Report of the Geological Survey Department, 1954. Pp. 32. Price, 2/50.

Ministerio de Minas e Hidrocarburos. Venezuela, 1954.

Año V, No. 17. Pp. xiv, 101. *Iron mining, diamonds, mining law, and economic mineral production data comprise this issue.*

Carnegie Institution of Washington. Washington, D. C., 1955.

Annual Report of the Director of the Geophysical Laboratory. Pp. 95–145. *Summary of a year's progress in research.*

French Bibliographical Digest: Crystallography—Mineralogy, 2. Pp. 102. No. 13, Series 2. **The Cultural Division of the French Embassy, New York, 1955.** *A sequel to the volume covering geology, this bibliography deals with post-war publications in crystallography and mineralogy. Free upon request.*

Das Steinkohlengebirge südlich Essen. R. TEICHMÜLLER. Pp. 16. E. Schweizerbart, Stuttgart, 1955. *Semi-technical guidebook to the stratigraphy of the Ruhr Valley with emphasis on coal (Pennsylvanian in age). Geologic map 1:25,000.*

SOCIETY OF ECONOMIC GEOLOGISTS

ANNUAL MEETING, 1956

New York City

The Annual Meeting for 1956 will be held February 20–23 in New York City at the Statler and New Yorker Hotels, in cooperation with the Annual Meeting of the American Institute of Mining and Metallurgical Engineers through the appropriate divisions of the Institute. Papers will be presented dealing with the economic geology of ore deposits, industrial minerals, and coal, as well as the application of geology to problems of ground water and engineering. Tentative plans include symposia on "Natural Concentration of Rare and Alloy Metals," "Ore Deposition and the Late Stages of Rock Crystallization," and "Chemistry of Ore Forming Fluids," with invited speakers.

The closing date for submission of papers for presentation will be December 20, 1955. Members of the Society wishing to present or to introduce papers for presentation should submit title of paper, name and address of author, and acceptable abstract (not over 250 words, a terse, concrete summary) to any one of the following: Olaf N. Rove, Secty., Society of Economic Geologists, at 30 East 42nd Street, New York 17, N. Y.; Chas. H. Behre, Jr., Chmn., Program Committee, S.E.G., at the Department of Geology, Columbia University, New York 27, N. Y.; or Edward H. Wisser, Chmn., Program Committee, Geology Subdivision, A.I.M.M.E., at 1986 Yosemite Road, Berkeley 7, California. To be considered for a place on the Society's program, authors must submit abstracts.

Program and Abstracts of Papers to be Presented at the Joint Meeting of the Society of Economic Geologists, the Geological Society of America, and Affiliates, New Orleans, La., U.S.A., November 7–9, 1955

SCIENTIFIC SESSIONS

The following listing includes all papers offered through the Society of Economic Geologists, as well as most of those having a clearly economic bearing offered through affiliated societies.

Whenever possible 5 minutes will be available for discussion of each paper.

MONDAY MORNING, L.S.U. MEDICAL SCHOOL AUDITORIUM

URANIUM DEPOSITS

Robert Wright and Phillip Merritt, *Cochairmen*

1. 9:00 Maurice Deul: *Mode of occurrence of uranium in the Chattanooga shale*
2. 9:15 Albert F. Trites, Jr.: *Mineralogy and geochemistry of the uranium deposits in the White Canyon area, San Juan County, Utah*

3. 9:30 Mary E. Thompson and Carl H. Roach*: *Mineralogy of the Peanut mine, Montrose County, Colorado*
4. 9:45 Alice D. Weeks: *Oxidation of the Colorado Plateau ores and its relation to recent geologic history*
5. 10:00 R. M. Garrels and C. L. Christ*: *Some aspects of the crystal chemistry of the oxidation of the Colorado Plateau uranium ores*
6. 10:15 Howard T. Evans, Jr.: *Vanadium mineral alteration sequences in relation to crystal chemistry and thermodynamics*
7. 10:30 R. C. Vickers: *Wall-rock alteration as a guide to carnotite deposits and their origin, northern Black Hills, South Dakota*
8. 10:45 N. L. Archbold: *Relationships of calcium carbonate to lithology and vandium-uranium deposits in the Salt Wash sandstone member of the Morrison formation*
9. 11:00 H. B. Wood* and W. David Grundy: *Techniques and guides for exploration of uranium-bearing Shinarump channels on the Colorado Plateau*
10. 11:15 George G. Witter, Jr.*, and Heinrich D. Holland: *Uranium mineralization of the Cal Uranium and Homestake Mines, Big Indian Wash, Utah*
11. 11:30 R. P. Fischer: *Vanadium and uranium in rocks and ore deposits*
12. 11:45 M. R. Klepper* and D. G. Wyant: *Geology of uranium*

MONDAY MORNING, INTERNATIONAL HOUSE

ENGINEERING GEOLOGY—I

PRODUCTS OF WEATHERING OF BEDROCK AND THEIR ENGINEERING PROPERTIES

SHAILER S. PHILBRICK and THOMAS F. THORNBURN, *Cochairmen*

1. 9:00 George A. Kiersch: *Rock weathering in Engineering Geology—Problems and need for research*
2. 9:20 William V. Conn* and George F. Sowers: *Engineering properties of bedrock weathering products in the Southeastern Piedmont*
3. 9:40 C. P. Holdredge: *Residual soils of the west slope of the Sierra Nevada and their engineering properties*
4. 10:00 Don U. Deere* and T. H. Thornburn: *Soil-mechanics properties of weathered volcanic rocks in Hawaii*
5. 10:20 T. H. Thornburn* and Don U. Deere: *Engineering problems associated with weathered limestone*

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6. 10:40 Robert F. Legget: *Permafrost near Lake Athabaska, Saskatchewan*
7. 11:00 John O. Nigra: *Engineering geology of the Thartar Project (Iraq)*
8. 11:15 Vladimir E. Wolkodoff: *Stress-strain relationships for igneous rocks*

BY TITLE

Portland P. Fox: *Exploration for the Cubatao underground powerhouse and pressure shaft, Brazil*

* Speaker.

MONDAY AFTERNOON, INTERNATIONAL HOUSE

ENGINEERING GEOLOGY—II

PROBLEMS OF ENGINEERING GEOLOGY IN THE MISSISSIPPI ALLUVIAL VALLEY

H. N. FISK and R. H. NESBITT, *Cochairmen*

1. 2:00 Harold V. Andersen: *Broad aspects of the application of geology to engineering projects in the Mississippi alluvial valley*
2. 2:00 Herman A. Huesmann: *Foundation problems during construction of Algiers Lock and Canal*
3. 2:40 Leo W. Hough: *Geological problems in highway engineering, Mississippi alluvial valley of Louisiana*
4. 3:00 Bramlette McClelland: *Foundation characteristics of Late Quaternary clays offshore near modern Mississippi delta*
5. 3:20 J. Bres Eustis: *Foundation engineering problems in New Orleans area*
6. 3:40 John R. Schultz: *Geological problems in the design and construction of flood-control structures in the Mississippi alluvial valley*

TUESDAY AFTERNOON, UNIVERSITY ROOM

MINERAL DEPOSITS—ORIGIN, EXPLORATION, USE

J. T. SINGEWALD, JR., and A. E. SANDBERG, *Cochairmen*

1. 2:00 Arthur Horen: *Mineralogy and petrology of the manganese protore at the Merid Mine, Minas Gerais, Brazil*
2. 2:15 P. K. Sims: *Paragenesis and structure of pitchblende-bearing veins, Central City district, Gilpin County, Colorado*
3. 2:30 Paul F. Kerr: *Geological observations from the Geneva Conference on Peaceful Uses of Atomic Energy*
4. 2:45 Fred L. Humphrey and Michael Wyatt*: *Scheelite in feldspathized granodiorite, Gabbs district, Nevada*
5. 3:00 Richard W. Hutchinson* and Richard J. Claus: *Pegmatite mineral deposits of the Alto Ligonha area, Portuguese East Africa*
6. 3:15 C. C. DeWitt: *Physico-chemical aspects of mineral deposition*
7. 3:30 Wolfgang E. Elston: *Volcanic succession and possible mineralization in the Dwyer quadrangle, southwestern New Mexico*
8. 3:45 M. Dean Kleinkopf: *Trace-element exploration of Maine lake water*
9. 4:00 T. S. Lovering: *Alteration near an acid halogen-sulfur fumarole*
10. 4:15 Wayne U. Ault: *Variations of sulfur isotopes in sulfide minerals*
11. 4:30 Gunnar Kullerud: *FeS–NiS system*

TUESDAY AFTERNOON, INTERNATIONAL ROOM

GENERAL SESSION WITH GEOLOGICAL SOCIETY OF AMERICA AND AFFILIATES

PAPERS OF GENERAL INTEREST

W. H. BUCHER and GORDON ATWATER, *Cochairmen*

1. 2:00 Isidore Adler* and J. M. Axelrod: *Application of fluorescent x-ray spectroscopy in geochemistry*

* Speaker.

2. 2:20 F. C. Canney,* A. T. Myers, and F. N. Ward: *Truck-mounted spectrographic laboratory for use in geochemical exploration—a preliminary report*
3. 2:40 Daniel I. Axelrod: *Altitude of the Sierra Nevada and western Nevada during Mio-Pliocene time*
4. 3:00 Rhodes W. Fairbridge: *Geotectonic significance of the continental shelves*
5. 3:20 John D. Moody * and M. J. Hill: *Wrench-fault tectonics*
6. 3:40 John W. Graham: *Evidence of polar shift since Triassic time*
7. 4:00 D. J. McLaren: *Carbonate bank deposits in the Devonian of the Alberta Rocky Mountains*
8. 4:20 Bruce C. Heezen: *Turbidity currents from the Magdalena River, Colombia*
9. 4:40 Luna B. Leopold: *Interrelation of river channel patterns—braided, meandering, and straight*

WEDNESDAY MORNING, GOLD ROOM

COAL I—PALEOBOTANY, STRATIGRAPHY, SEDIMENTATION

J. M. SCHOPF and J. W. HUDDLE, *Cochairmen*

1. 9:00 P. A. Hacquebard: *Lower Carboniferous spore assemblage in coal from the South Nahanni River area in northwestern Canada*
2. 9:20 Aureal T. Cross * and Mart P. Schemel: *Allegheny-Lower Conemaugh stratigraphy in northern West Virginia*
3. 9:35 Fred Cropp,* R. M. Kosanke, and H. R. Wanless: *Pennsylvanian rocks and spore floras from the subsurface Warrior Basin, Mississippi*
4. 9:55 Gerhard O. W. Kremp: *Microflora investigations in Tertiary and Mesozoic strata of Europe, especially of Germany*
5. 10:15 E. C. Dapples * and R. M. Mitchum: *Petrographic characteristics of sandstones of the Pennsylvanian of the Central Appalachian coal field*
6. 10:30 John C. Ferm * and J. W. Huddle: *Slumps and mud flows in rocks of Pennsylvanian age in the Appalachian Plateau*
7. 10:50 Walter V. Searight: *Stratigraphic pattern in pre-Marmaton Desmoinesian cycles*
8. 11:05 Henry H. Gray: *Stratigraphic nomenclature in coal-bearing rocks*
9. 11:20 William H. Smith * and Russell A. Brant: *Utilization of business machine-tabulations for the systematic classification of geologic data*

WEDNESDAY AFTERNOON, GOLD ROOM

COAL II—PETROGRAPHY AND CONSTITUTION

R. M. KOSANKE and W. SPACKMAN, *Cochairmen*

1. 2:00 Gilbert H. Cady and Gilbert E. Smith *: *Exploration of the petrographic constitution of four Ohio coals*
2. 2:20 Norman Schapiro * and Aureal T. Cross: *Petrography and regional characteristics of the Lower Kittanning coal*

* Speaker.

3. 2:40 J. M. Schopf * and R. J. Gray: *Concept, technique, and language in coal petrology*
4. 3:00 Raymond Siever: *Variation of coal reflectance*
5. 3:15 Irving A. Breger: *Association of uranium with a naturally occurring coal extract*
6. 3:30 Taisia Stadnichenko,* Peter Zubovic, and Elizabeth L. Hufschmidt: *Minor elements in the ash of coals from western Kentucky, Indiana, and Illinois*

BY TITLE

John A. Harrison: *Petrographic components and stoker coal testing*
Margaret A. Parker: *Computation of chemical analyses of coal speeded by use of IBM punched cards*

Abstracts of Papers Concerned with Economic Geology to be Presented at the Meeting

APPLICATION OF FLUORESCENT X-RAY SPECTROSCOPY IN GEOCHEMISTRY

ISIDORE ADLER AND J. M. AXELROD

U. S. Geological Survey, Geochemistry and Petrology Branch, Washington 25, D. C.

A four-channel X-ray spectrograph and an associated electronic system for measurement have been designed and built in the U. S. Geological Survey and have proved to be a powerful tool in the collection of analytical data on rock, mineral, and soil samples. This device makes possible the determination of up to four elements simultaneously. A curved crystal spectrograph has also been built and is being used for the study of small samples, single crystals, and X-ray diffraction spindles.

Rapid analytical methods have been developed for determining uranium, niobium, tantalum, rubidium, cesium, and selenium in rock samples. Internal standardization has made it possible to deal with widely varying base materials. A quantitative analysis for elements such as thorium can be performed in as little as an hour. Application to geochemical prospecting problems indicates results can be obtained in 2 to 3 minutes per sample. This has been demonstrated by the determination of lead and zinc in soil samples with a lower limit for zinc of 50 parts per million and lead 75 to 100 parts per million.

BROAD ASPECTS OF THE APPLICATION OF GEOLOGY TO ENGINEERING PROJECTS IN THE MISSISSIPPI ALLUVIAL VALLEY

HAROLD V. ANDERSEN

School of Geology, Louisiana State University, Baton Rouge, Louisiana

The stability of the sediment either as a foundation material or to withstand stream erosion is the principal concern of the geological engineer working in the Mississippi River Valley. In the Gulf of Mexico and on the highlands adjacent to the alluvial valley of the Mississippi River where the sediments are principally sands, silts and massive clays, most materials are competent and stream erosion is

* Speaker.

negligible. In the alluvial valleys, however, where the sediment ranges from gravel to organic muck, unsuitable foundation materials may be encountered and stream erosion may be difficult to control. This is the sedimentary province of the Mississippi River Valley with multifarious geological engineering problems.

The principal physiographic elements found in an alluvial valley are: backswamps; levees; abandoned stream channels; and, occasionally, terrace remnants isolated from the adjacent highlands. These physiographic elements are, in general, characterized by certain sized clastics, stream deposited and subject to reworking by the stream occupying the alluvial valley. The backswamps consist of clays and silts, or occasionally, organic mucks. The levees and terraces are composed principally of silt although sand and gravel are present in some of the terraces. The abandoned channels contain sands, silts and clay, the latter often in the form of "plugs" which may eventually control the meander belt of the stream. These physiographic elements of the alluvial valley grade laterally into and overlap each other to form complex sedimentary sequences which the engineering geologist is obligated to evaluate.

RELATIONSHIPS OF CALCIUM CARBONATE TO LITHOLOGY AND VANADIUM-URANIUM DEPOSITS IN THE SALT WASH SANDSTONE MEMBER OF THE MORRISON FORMATION [1]

N. L. ARCHBOLD

Box 360, U. S. Geological Survey, Grand Junction, Colorado

A study was made to determine whether there are any relationships between $CaCO_3$ content and lithology or between $CaCO_3$ and vanadium-uranium deposits in the Salt Wash sandstone member of the Morrison formation. The $CaCO_3$ content was determined for more than 600 samples from the Salt Wash sandstone member. In addition, 140 chemical assays of mineralized rock were obtained for study.

The studies indicate that altered gray-green mudstone contains less $CaCO_3$ than unaltered red-brown mudstone, and that sandstone contains more $CaCO_3$ adjacent to contacts with mudstone. No difference was indicated between $CaCO_3$ concentrations in altered light-gray sandstone and unaltered light-red sandstone.

The concentration of $CaCO_3$ and the grade of mineralized rock do not appear related. The $CaCO_3$ concentrations do, however, seem to parallel ore whether in bedded or roll form. Calcium carbonate is probably redistributed during mineralization.

VARIATIONS OF SULFUR ISOTOPES IN SULFIDE MINERALS

WAYNE U. AULT

Lamont Geological Observatory (Columbia University), Palisades, New York

A study of sulfide minerals has shown some variations larger than heretofore reported. Pyrrhotite showed the greatest depletion in S^{34} relative to meteoritic sulfur, with a spread (2.9%) comparable to that of pyrite but in the opposite direction. Pyrrhotites may be classed as magmatic or hydrothermal based on trace element analysis but the sulfur isotopic ratio does not appear to be definitive of origin.

[1] Publication authorized by the Director, U. S. Geological Survey and the U. S. Atomic Energy Commission.

The sulfur isotopic ratio S^{34}/S^{32} was determined for several suites of galena samples from various localities in the Mississippi Valley for which the lead isotopic composition was known. The variation in the isotopic composition of sulfur in the galenas is much smaller and not consistent with that of the lead. This suggests that the variations in the lead isotope abundances are not due to fractionation. There are some regional differences even in the Mississippi Valley deposits.

ALTITUDE OF THE SIERRA NEVADA AND WESTERN NEVADA DURING MIO-PLIOCENE TIME

DANIEL I. AXELROD

Dept. of Geology, University of California, Los Angeles

Twenty-odd Mio-Pliocene floras distributed from sea level in west-central California, across the Sierra Nevada and into western Nevada occur either (a) at or near the base of the late Tertiary Sierran andesite (Mehrten formation, Kate Peak andesite) and its equivalents to the east and west, or (b) in the underlying Valley Springs formation and its close correlatives in western Nevada and coastal California.

Since the floras are related to living communities whose topographic and climatic relations can be measured, they provide a basis for estimating the altitude of the Sierra Nevada and of west-central Nevada during Mio-Pliocene time. Local, provincial and regional comparisons indicate there were only moderate east-west differences across this transect where environmental diversity is marked today.

Paleogeographic inferences include: *Topographic*—Just prior to late Tertiary vulcanism the Sierra Nevada was the site of a broad ridge whose summit lay near 3,000 feet. The lowlands of west-central Nevada had an average elevation near 2,000 feet. *Climatic*—Building-up the Sierran ridge over 6,000 feet in post-Mio-Pliocene time (a) lowered rainfall over the lowlands to leeward sufficient to account for the present desert, and (b) reduced temperatures along its summit so that an arctic-alpine zone came into existence. *Biologic*—Plants and animals gradually invaded these developing *new zones* during late Cenozoic time from contiguous milder environments, areas in which the present-day types of the extreme environments find most of their relatives.

THE ASSOCIATION OF URANIUM WITH A NATURALLY OCCURRING COAL EXTRACT

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Uranium and vanadium are associated with several types of carbonaceous material on the Colorado Plateau. Besides coalified wood and crude oil, there is also a black, lustrous carbonaceous material that usually contains sufficient uranium to classify it as an ore. No cellular structure has been identified in this material, which occurs either as an impregnation in sandstone or as pellets ranging from several millimeters to several centimeters in diameter. In some regions the material—variously called asphaltite, thucholite, or glance pitch in the literature—is in apparent association with crude oil, leading to the suggestion that it is a petroleum residue. Because of its apparent importance in the geochemistry and emplacement of uranium on the Colorado Plateau, investigations of this material have been carried out in some detail.

Ultimate analysis, differential thermal analysis, and infrared absorption analysis all show the carbonaceous material to be similar to a low-rank coal in composition and chemical structure and to be unlike other asphaltites such as gilsonite or wurtzilite. Autoradiographic studies also show that the uranium is nearly homogeneously dispersed in the carbonaceous matter. The evidence obtained to date shows that this so-called asphaltite is not related to crude oil but rather is a coal extract derived from coalified wood in the region and precipitated under the proper physical and chemical conditions. The highly insoluble nature of the coal extract is thought to result from cross-linkage of coal molecules as a result of irradiation by alpha particles.

AN EXPLORATION OF THE PETROGRAPHIC CONSTITUTION OF FOUR OHIO COALS *

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Since July 1953 an exploration of the petrographic constitution of four Ohio coals, Meigs Creek (No. 9), Pittsburgh (No. 8), Middle Kittanning (No. 6) and Clarion (No. 4A), has been underway at Columbus. The methods of investigation have been restricted almost entirely to those of polished surface technique largely because the investigation included a study of broken coal as well as of columns and cores. The investigation involved the preparation of megascopic bed profiles in terms of the banded ingredients and mineral matter, these generalized profiles indicating considerable differences in the composition of the four beds. Profiles were also made of whole beds or selected portions of bed on the basis of microscopically identified constituents or macerals. Such profiles further accentuated the differences among the coals, particularly with respect to the duller portions of the beds, the character and degree of dullness being determined by varying quantities of exinite, micrinite (opaque matter) and mineral matter and decrease in content of microvitrain and vitrinite as represented by the humic degradation matter. Studies of broken coal produced by dropping or representing screen sizes of mine run coal indicated that the physical character, particularly hardness and toughness, of the so-called lithotypes and microlithotypes exercsied an important influence upon the petrographic composition of the various sizes. It seems probable that, where it is essential to maintain uniformity of product prepared for special use, consideration of the petrographic composition of the coal in planning preparation procedures would have a beneficial result.

A TRUCK-MOUNTED SPECTROGRAPHIC LABORATORY FOR USE IN GEOCHEMICAL EXPLORATION—A PRELIMINARY REPORT

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A mobile spectrographic laboratory to demonstrate the feasibility of using and transporting spectrographic equipment in the field and to supply rapid on-the-spot analytical data is housed inside a 7 by 12 foot insulated and air-conditioned van-type truck body and carries complete equipment for making qualitative and quantitative spectrographic analyses of geological materials. The spectrograph is a fixed-position 1.5-meter grating instrument in a Wadsworth stigmatic mounting, which

* Presented with the approval of the Chief, Ohio Division of Geological Survey.

records the region from 2063A to 4837A in the second order on a 20-inch strip of film. Companion units include a projection-type comparator-densitometer, film processor, and other accessory equipment. Trailer-mounted motor generators supply 230 volts d-c for the arc source unit and 115 volts a-c for lights and accessories.

In June 1955 the truck-mounted laboratory was driven 525 miles to a field project near Eureka, Utah. During the trip, all of the equipment remained in good adjustment, and the laboratory was ready for operation in less than 2 hours after arrival.

Because of the large number of elements that can be determined from a single spectrogram, the truck-mounted spectrographic laboratory should be useful in the early stages of a geochemical exploration project to determine diagnostic suites of elements, and later, to guide the day-to-day sampling.

ENGINEERING PROPERTIES OF BEDROCK WEATHERING PRODUCTS IN THE SOUTHEASTERN PIEDMONT

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The gneisses, schists, and associated crystalline rocks of the Southeastern Piedmont have been subjected to the rapid chemical weathering typical of a warm humid climate, and have broken down to form the deep residual soils of the area. Analyses of the soils indicate alteration of the original minerals to secondary minerals which are largely kaolinite, illite, vermiculite, quartz, gibbsite, biotite, and iron oxide. Feldspars, which constitute a large percentage of the original minerals, are often completely altered, even adjacent to unweathered rock. The normal soil profile, produced by varying degrees of weathering with depth, consists of red, sandy to silty surface clays, grading into micaceous sandy silts and silty sands, which in turn become gradually less altered, with inclusions of unweathered rock, as the sound rock surface is approached.

The soils produced by this type of weathering present unique construction and engineering problems. The bands and lenses of varying types of soil material which are inherent from the gneissic structure of the parent rock, and the varying degrees of alteration present in each material, make foundation analysis procedures by normal soil mechanics methods difficult. Foundation design must consider contorted bands of soft, partially altered minerals which complicate bearing capacity and settlement computations. Construction procedures must also be planned with an understanding of soil and rock characteristics to prevent costly and often dangerous slope failures in excavations.

PENNSYLVANIAN ROCKS AND SPORE FLORAS FROM THE SUBSURFACE WARRIOR BASIN, MISSISSIPPI

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Although outcropping Pennsylvanian strata of the Black Warrior basin in Alabama aggregate only about 3,700 feet, borings in northeastern Mississippi suggest a thickening to more than 8,000 feet within three counties of their outcrop under Cretaceous sediments. Wells have entered Pennsylvanian rocks as far as two counties south of the maximum penetration in Clay County, beyond which Ordovician dolomites are found beneath the Cretaceous. Samples from three wells in Monroe, Calhoun and Clay counties represent respectively 2,105, 4,736 and 8,013

drill feet of Pennsylvanian strata. Well cuttings in each yield coal chips which may be separated from associated shale and sandstone by specific gravity.

The Young-Hendeson well in Clay County yields coal from 50 different samples or adjacent groups of samples, suggesting at least 50 coal beds. Althought the amount of coal recovered from each zone is generally less than one gram, spores have been isolated by maceration, and it is believed they can be used for correlation. The highest coal zone in the Clay County well contains *Denso-sporites* which is not known to extend above the Tradewater of Illinois or the top of the Pottsville or basal Allegheny of the Appalachian field. *Cirratriradites maculatus* was also observed in this highest coal zone and is not known to occur above the Tradewater in Illinois. Thus the stata of Pottsville age suggest an aggregate of at least 8,000 feet. The coal succession in Mississippi seems likely to yield the most complete succession of Pottsville age spore floras in the United States.

ALLEGHENY–LOWER CONEMAUGH STRATIGRAPHY IN NORTHERN WEST VIRGINIA

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Five locally minable but highly variable coal seams and several marine zones in Allegheny and Lower Conemaugh strata of the Northern Panhandle of West Virginia and adjacent areas in Ohio and Pennsylvania have been the basis for interstate correlation of these strata for many years. Knowledge of faunal assemblages for ready and accurate identification of the marine zones has not been established.

Recent studies of plant microfossils from coal samples taken from core tests, oil-well cuttings, and outcrops make it possible to differentiate Lower and Middle Kittanning coals from each other and these two from the Freeport coals. The Upper and Lower Freeport coals are usually individually identifiable and these are both distinctive from Brush Creek and Bakerstown Assemblages.

Extensive study of surface outcropping sections and detailed analyses of numerous sets of well-cuttings have made it possible to outline the general extent of five principal coals and shows them to change rapidly in thickness within very local areas. Some problems of nomenclature or/and correlation remain unsolved because of the apparent misidentification of Kittanning, Freeport and Mahoning coals, between this area and the type areas in Pennsylvania and Ohio and even the ambiguity of coal identification at type localities. Moreover, additional coal horizons with local thick coals further confuse the correlation.

Several additional marine horizons are now recognized. Marine conditions appear to have returned between accumulation of most coal seams in the area. Some of these were minor pulsations, often two or three for each major invasion, e.g., Kittanning, Freeport, Brush Creek, Cambridge and Ames.

PETROGRAPHIC CHARACTERISTICS OF SANDSTONES OF THE PENNSYLVANIAN OF THE CENTRAL APPALACHIAN COAL FIELD

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Pennsylvanian sandstones associated with coals of the Lee group in the Central Appalachian Coal Field constitute a continuous petrographic series ranging from

graywackes in the extreme eastern part to quartzose varieties which predominate in the west, bordering the Nashville dome.

Rocks classified as graywackes have an average composition of 50% quartz, 10% feldspar (70% microcline and 30% sodic plagioclase), 20% matrix (clay, sericite, chlorite, quartz, carbonaceous matter), and 20% rock fragments. Subgraywackes average 72% quartz, 26% matrix of finely divided quartz, sericite and carbonaceous matter, 10% rock fragments, and less than 1% feldspar. Quartzose sandstones average 90% quartz grains, 5% matrix (sericite and clay), and 5% rock fragments. Rock fragments are quartzite and shale.

Lateral gradation exists between graywackes and subgraywackes, and vertical as well as lateral gradation is observed between subgraywackes and quartzose sandstones.

Each petrographic variety displays paragenetic relationships among minerals, apparently reflecting diagenetic environmental conditions. Graywackes show fresh microcline, but altered sodic plagioclase. Silica is unstable as indicated by the highly frayed edges of quartz, but potash rich minerals are stable, and others, such as sericite develop from the clay matrix.

Quartz in subgraywackes shows secondary development which is inhibited by the presence of clay matrix. In this rock silica is stable and where quartz grains are in contact overgrowths form. Potash minerals particularly muscovite grow as large secondary crystals in the clay matrix. Carbonate cement, generally iron rich, replaces quartz grains, and where concentrated develops concretions. Local calcite cement is replaced by secondary silica during time of development of quartz overgrowths.

Quartzose sandstones show tendency to increase in carbonate content (primarily calcite) until carbonate preponderates over quartz. In such cases quartz appears unstable and is being replaced by calcite. Where carbonate cement is feeble quartz overgrowths are very common and interlocking of grains results.

SOIL MECHANICS PROPERTIES OF WEATHERED VOLCANIC ROCKS IN HAWAII

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Construction operations in the Hawaiian Islands have revealed the unusual engineering characteristics of residual soils derived from volcanic rocks. Weathering in the tropical to sub-tropical climate has proceeded to depths of more than 100 ft. in some places. X-ray diffraction studies show that the residual soils which have developed are composed essentially of amorphous material with little or no identifiable clay mineral. This composition is similar to the clay from Mexico City which is also derived from volcanic parent materials.

The natural water contents of the Hawaiian residual soils are high, ranging from 50 to 300% based on oven-dry weight. One of the peculiar properties noted is the change in the Atterberg limits upon drying from the natural to the air-dry state. The values of the liquid limit and the plasticity index decrease by as much as 100%.

The compaction characteristics are also dependent upon the moisture conditions. Laboratory values of dry density obtained from tests starting with air-dry material are from 20 to 50% greater than values obtained in the field using the soil at its natural water content. Most of these soils appear to be highly sensitive to disturbance of their natural structure. The unconfined compressive strength of undisturbed samples may be 9 or more times as great as the strength of samples which have been remolded at their natural water contents.

MODE OF OCCURRENCE OF URANIUM IN THE CHATTANOOGA SHALE

MAURICE DEUL

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Uranium in the Chattanooga shale exists largely as a colloidal phase dispersed through the organic matrix. Most of the uranium is not at present combined with the organic material nor is it combined with the minerals. Three lines of evidence lead to the conclusion that the uranium is present as a dispersed colloidal phase, perhaps as an oxide:

I. After comminution to colloidal size by ball-mill grinding in mixed liquid media, organic concentrates and mineral concentrates are lower in uranium content than the original shale, but a middlings fraction, containing colloidal particles not readily concentrated with the other fractions, has a threefold concentration of uranium over that in the original shale.

II. Fine grinding of dry shale in an air-jet pulverizer, followed by air elutriation, leads to separation of a fine fraction in which uranium is enriched by 36 percent over the original shale. In this work no effort was made to separate mineral and organic fractions.

III. Dialysis of a colloidal suspension of shale in water to remove ionic material yielded a product having a twofold concentration of uranium over the original shale.

Analyses for uranium, carbon, hydrogen, and ash and mass balances support the experimental work.

SOME PHYSICO-CHEMICAL ASPECTS OF MINERAL DEPOSITION

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A theory of mineral deposition is developed which depends solely on the known physical and chemical properties of the atoms comprising the minerals. It is postulated that surface atoms of minerals are but partially bound to adjacent atoms. Metallic atoms act as electron sinks; nonmetallic atoms act as electron donors. Elements of groups V_b and VI_b of the Periodic Table are potential electron donors. Such atoms in a mineral surface attract other metallic ions, e.g.:

$$Cu^{++} + Cu:\ddot{\underset{\cdot\cdot}{S}}: \rightarrow [Cu:\ddot{\underset{\cdot\cdot}{S}}:Cu]^{++} + 2\ominus \rightarrow Cu:\ddot{\underset{\cdot\cdot}{S}}:Cu$$

$$Cu^{++} + Fe:\ddot{\underset{\cdot\cdot}{S}}::\ddot{\underset{\cdot\cdot}{S}}: \rightarrow [Fe:\ddot{\underset{\cdot\cdot}{S}}::\ddot{\underset{\cdot\cdot}{S}}:Cu]^{++} + 2\ominus \rightarrow Fe:\ddot{\underset{\cdot\cdot}{S}}::\ddot{\underset{\cdot\cdot}{S}}:Cu$$

For stability the positively charged chalcocite and chalcopyrite ionic molecules require free electrons to neutralize the positive charge. Two general forms of pyrite are known—is there more than one form of chalcopyrite?

Pentlandite, $(FeS)_2.NiS$, could be formed thus:

$$Fe^{++} + Fe:\ddot{\underset{\cdot\cdot}{S}}::\ddot{\underset{\cdot\cdot}{S}}: + Ni:\ddot{\underset{\cdot\cdot}{S}}: \rightarrow [Fe:\ddot{\underset{\cdot\cdot}{S}}::\ddot{\underset{\cdot\cdot}{S}}:Ni:\ddot{\underset{\cdot\cdot}{S}}:Fe]^{++} + 2\ominus$$

$$\rightarrow Fe:\ddot{\underset{\cdot\cdot}{S}}::\ddot{\underset{\cdot\cdot}{S}}:Ni:\ddot{\underset{\cdot\cdot}{S}}:Fe$$

Query: Are there as many as four forms of pentlandite; does crystal habit limit to one form?

Thus pyrrhotite is found associated with small amounts of many metallic atoms. Oxidation of intermediate noble metal sulfides and tellurides leaves the noble metal free.

Ionic adsorption involves the creation of acidic conditions. This evidence should be looked for in or adjacent to every mineral deposit.

The overburden of important metallic sulfide deposits usually contains small amounts of a like metallic silicate. Oxidation, leaching, zeolitic fixation is followed by enriched secondary metallic sulfides in increasing concentration down to the main deposit lying on an impenetrable bedrock or clay. Porous rock or shale allows enriched sulfide and silicate coexistence at the lower levels, e.g., New Mexico, Arizona, Utah porphyry copper deposits.

VOLCANIC SUCCESSION AND POSSIBLE MINERALIZATION IN THE DWYER QUADRANGLE, SOUTHWESTERN NEW MEXICO [1]

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The Dwyer quadrangle lies southeast of the Santa Rita-Central mining districts. Potentially mineralized pre-Tertiary rocks are largely covered by late Tertiary volcanics and Tertiary-Quaternary valley fill.

The volcanics, up to 8,000 feet thick, belong to two suites separated by an unconformity. The older volcanics grade from andesine-pyroxene andesites to andesine-amphibole latites to quartz-sanidine-oligoclase-biotite rhyolites. The rhyolites consist mainly of tuffs and ignimbrites. There are many erosional intervals within this succession, but none are accompanied by significant chemical changes. The entire older suite has calc-alkaline aspect, and possibly developed through fractional crystallization from a granodioritic magma, similar to that of many Laramide intrusives in the region.

The younger volcanics, of calcic aspect, include four basalt and olivine andesite units, a rock on the rhyolite-latite-trachite boundary, and two minor rhyolites more calcic than those of the older suite. One of the andesites shows evidence of contamination by silicic material. All units of the younger suite are separated by erosional disconformities, each corresponding to a chemical change.

At least three intra-volcanic and one post-volcanic period of faulting have been recognized. Faults follow the northeast and northwest trends of pre-volcanic (Laramide) faulting, and therefore parallel the fractures controlling mineralization in the Santa Rita-Central districts. However, the volcanics are almost everywhere too thick for profitable prospecting.

FOUNDATION ENGINEERING PROBLEMS IN NEW ORLEANS AREA

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Substrata in the Greater New Orleans area are represented by two principle geologic formations: a Recent deposit of soft peats, organic clays and clays with layers and lenses of fine sands, and a late Pleistocene deposit of stiff to medium stiff clays and dense sands.

The Recent extends from the ground surface to depths ranging from 45 to 110 feet. The Pleistocene is usually oxidized for depths of 5 to 25 feet below the top of the bed and readily recognized by its distinct tan and gray color.

Basic problems confronting designers, as in other municipalities, are determination of either the allowable soil bearing value or safe pile load capacity. The major problem in New Orleans however is how to eliminate, or at least minimize, the

[1] Given by permission of the Director, New Mexico Bureau of Mines and Mineral Resources.

settlement of structures caused by consolidation of clay strata located principally in the Recent formation.

Support of structures on piles is commonplace. Major structures are usually founded on either deep piles to Pleistocene or on piles into dense sand stratum in Recent material when present. Preloading of some warehouse areas has been used with success thereby eliminating pile foundations for floors. Spread footings are used satisfactorily for small buildings within the areas of natural levee deposits adjacent to the Mississippi River. Use of footings in areas distinct from the river results in most cases in settlement and cracking in varying amounts depending on depth to, and thickness of underlying peats and organic clays. More recently, slab foundations on compacted fill have proven successful for residences.

VANADIUM MINERAL ALTERATION SEQUENCES IN RELATION TO CRYSTAL CHEMISTRY AND THERMODYNAMICS

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All available thermodynamic and chemical data have been drawn upon to compile a phase diagram in the oxidation potential-pH field for vanadium in aqueous solution. Regions in which trivalent, tetravalent, and pentavalent states of vanadium are stable lie within range of the natural conditions existing in the Colorado Plateau area. The chemical properties and mineral associations of the various vanadium minerals allow each species to be associated with specific stability regions on the phase diagram and permit alteration sequences to be traced. The chief primary vanadium ore mineral is montroseite, which forms the focus of the alteration phenomena. Montroseite is converted by weathering processes to paramontroseite, corvusite, pascoite and hewettite, under acid conditions. Under more alkaline conditions, paramontroseite may be converted to two new minerals, $VO(OH)_2$ and $CaV_5O_9.5H_2O$, and then successively to melanovanadite and rossite.

GEOTECTONIC SIGNIFICANCE OF THE CONTINENTAL SHELVES.

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A Continental shelf is viewed essentially as a geomorphic concept, its limits ranging from zero up to great widths and depths, even to 500 miles and 500 fathoms deep. Seen in perspective of geological time, it ranges from the inner edge of the coastal plain to the outer shelf edge, between which periodically oscillates the littoral belt, conditioned by eustatic and tectonic events.

In the past, the shelf has been variously regarded as a sedimentary wedge, a wave-bevelled terrace, or as a "quarry and tip" or combination feature. Field studies in Australia, with analogies drawn from North America, Europe and the Middle East, suggest that not one theory, but all may be applied in different areas. The hypsographic curve indicates a bevel and wedge combination, an average for the Earth, but geotectonic history of areas varies the effect: long stability increases the bevel, instability increases the size of the sedimentary wedge.

Shelves represent the site of most contemporary sedimentation and over 90% of sediments in the geologic column are neritic. Filling both para- and ortho-geosynclines, which may possess bathyal or abyssal depths, sediments initially deposited on the shelf are transported into the deeps by waves, current, density flow, gravity slump and ultimately by major tectonic slide (often so-called nappe overthrusts).

Tide gauge work indicates that almost all sedimentary shelves are subsiding today; most rocky shelves are stable or rising. With alternation in geologic periods between thalassocratic and epeirocratic episodes (eustatic controls), there will be an oscillation of the axis of subsidence from the inner edge of the shelf to the slope and back.

SLUMPS AND MUD FLOWS IN ROCKS OF PENNSYLVANIAN AGE IN THE APPALACHIAN PLATEAU

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Deformed rocks interpreted as the result of penecontemporaneous slump and mud flow are common in rocks of Pennsylvanian age in the Appalachian Plateau. Reconnaissance in Pennsylvania, Ohio, West Virginia, Kentucky, and Tennessee located many examples ranging in age from oldest to youngest Pennsylvanian. In individual areas of detailed study in Pennsylvania and Kentucky, deformed rocks occur in as many as 50% or as few as 15% of the exposures examined. Examples are much more numerous and occur in a larger area than previously reported.

The observed zones of deformed rocks range in thickness from one inch to 70 feet and in horizontal extent from a few feet to 4½ miles. They are limited at the top and bottom by undisturbed strata. Features seen in deformed zones include normal and reverse faults, belts of complex shearing, folds, ellipsoidal masses of rolled up sediments, transported blocks, and massive beds with poor grain orientation. These features represent rigid, plastic, and fluid behavior of sediments under stress. On the basis of these stress reactions, two general types of deformed strata, slump and mud flow, are distinguished. Slumps include strata which deformed rigidly by simple or complex faulting and plastically by folding. Mud flows include strata which deformed mainly as fluids and partly as plastics.

VANADIUM AND URANIUM IN ROCKS AND ORE DEPOSITS *

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Trace amounts of vanadium and uranium are common in both igneous and sedimentary rocks. Vanadium is more abundant in basic igneous rocks, uranium in the acidic ones. Both metals tend to concentrate abnormally in sedimentary rocks containing organic material.

With few exceptions, vanadium does not tend to concentrate in hypogene ore deposits. Its average concentration in 775 samples of ores and mill products is less than 100 ppm, which is less than the reported average content in igneous rocks and shales. It appears in similarly low concentrations in hot-spring precipitates and solutions. Of the exceptions among hypogene vein deposits containing some vanadium, two types that may have escaped specific notice previously are those in which vanadium is associated with titanium and with tellurium.

Apparently vanadium is equally sparse in hypogene deposits that contain uranium ore. Vanadium is not mentioned in published geologic reports on most productive uranium-bearing veins, perhaps because its content is too low to form easily recognized vanadium-bearing minerals. Available spectrographic determinations of samples of uranium-bearing veins show an average vanadium content no greater than the average concentration in the samples of ores and mill products.

* Publication authorized by the Director, U. S. Geological Survey, and by the U. S. Atomic Energy Commission.

Thus vanadium apparently does not tend to concentrate in the normal hypogene environment, and specifically it does not appear to concentrate in most hypogene veins containing uranium ore. If this is true, unusual processes and conditions might be required to explain a hypogene source of vanadium and uranium in deposits containing commercial concentrations of both metals.

EXPLORATION FOR THE CUBATAO UNDERGROUND POWERHOUSE AND PRESSURE SHAFT, BRAZIL

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This underground powerhouse, the third to be completed in Brazil since 1953, consists of six units of 65,000 KVA each operating from a single pressure shaft under a head of 715 meters. It is located in the escarpment of the Serra do Mar 16 kilometers northwest of Santos, Brazil.

Although a detailed geologic study of the region revealed no serious bedrock defects that would cause construction problems in the Archean gneisses and Algonquin quartzites, marbles, and phillites, it was deemed advisable to make an extensive investigation of the subsurface conditions by a number of diamond core drill holes along the pressure shaft and in the proposed locations of the powerhouse. Thirty-three holes, having a total of 3,352.95 meters, were drilled. Five of the holes exceeded 200 meters in depth and one attained a depth of 290 meters. Not all the holes penetrated to the full depth of the pressure shaft if there were no serious bedrock defects encountered in the first 50 meters. This saved considerable drilling. A core hole spacing of 100 meter center proved to be adequate because of favorable geologic conditions. The deeper holes deviated as much as 25 degrees from the vertical at the bottom. AX-size holes proved to be adequate for the hard rocks encountered and saved considerable cost over the larger sizes.

The excavation was completed for the powerhouse and pressure shaft without the use of any supports, but some quartzite in the powerhouse area was quite blocky and roof bolts were used extensively.

SOME ASPECTS OF THE CRYSTAL CHEMISTRY OF THE OXIDATION OF THE COLORADO PLATEAU URANIUM ORES

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Uraninite and coffinite are the major primary uranium minerals of the Colorado Plateau deposits. Both oxidize to yield U^{+6} before reacting significantly with other mineral constituents. In the absence of pentavalent vanadium, arsenic, and phosphorus, uranium forms relatively soluble carbonate or sulfate complexes. In the presence of pentavalent vanadium, arsenic, and phosphorus, uranium is fixed in insoluble layer structure compounds formed by union of uranyl ion with orthovanadate, orthophosphate, or orthoarsenate. Uranium is also fixed by silica as uranyl silicate and by adsorption on hydrous iron oxides. Emphasis in the present study is on the relationship of structural crystallography to the paragenesis of the oxidation products.

EVIDENCE OF POLAR SHIFT SINCE TRIASSIC TIME

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The magnetizations of 343 samples of Permian and Triassic sediments from the United States (southwest, mainly) are compared to magnetizations that have been regorted by Clegg, Almond and Stubbs (Phil. Mag., **45**, 583, 1954) for sediments of approximately the same age in England. An impressive number of the observations are in agreement simply on the basis of assuming that the rocks were magnetized by a geomagnetic field about like the one today, the essential difference being that this field was in a significantly different orientation. Other rock magnetism observations and theoretical considerations indicate that it is not fortuitous that the magnetic and geographic axes nearly coincide today. Hence it can be said that the correlation of the English and American magnetizations suggests that an outer shell of the earth has been translated relative to the rotation axis. In the former orientation the equator would cross Lower California, Arkansas, Massachusetts, Gibraltar, Kenya and Tasmania. Observations from other continents are necessary for determining the extent to which the outer shell held together as a unit during the translation. The causes for the shift and the time during which it took place are not known.

STRATIGRAPHIC NOMENCLATURE IN COAL-BEARING ROCKS

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Rock units most practicable for mapping of coal-bearing rocks extend from the top of one coal bed to the top of the coal next above. Where the coal is missing, the stratigraphically equivalent position may be fixed by characteristic associated rocks such as underclay or roof shale. The name *cyclothem* is retained for this mappable rock unit to emphasize its cyclic and coal-bearing aspects.

Cyclothems are better characterized by lateral relationships between rock types than by a single synthetic vertical succession, because no rock type is coextensive with the cyclothem. The boundary of the cyclothem is not of universal extent because the identifying rocks may wedge out or grade laterally into indeterminate types; the resulting rock unit, consisting of two or more cyclothems locally coalesced, may be called a concyclothem. Coal beds locally present within a cyclothem divide the cyclothem into intracyclothems, identical to but smaller than cyclothems both in thickness and extent.

Most coal beds are named; cyclothems, concyclothems, and intracyclothems may therefore be named for the coal beds included at their tops.

A LOWER CARBONIFEROUS SPORE ASSEMBLAGE IN COAL FROM THE SOUTH RIVER AREA IN NORTHWESTERN CANADA *

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Field relations in the South Nahanni river area, situated in the N.W.T. at 123°59′ west and 61°06′ north, indicated the presence of a Carboniferous coal

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deposit.[1] Such deposits have not previously been reported from western Canada, the known Carboniferous strata being of marine or near shore deposition.

The small spore assemblage from this coal contains numerous types that greatly vary in form and sculpturing. Those with equatorial thickenings and ridges, belonging to the suite *Cingulati* Potonie and Klaus 1954, predominate. In all 15 genera and 58 species are recognized, including 3 new genera, 35 new species and 10 new types of which only one or two specimens were found.

The following known genera are present, with the number of species in brackets: *Calamospora* (2); *Punctati-sporites* (10); *Granulati-sporites* (2); *Reticulati-sporites* (3); *Triquitrites* (3); *Tripartites?* (1); *Lycospora* (2); *Simozonotriletes* (1); *Denso-sporites* (12); *Cirratriradites* (2); *Reinschospora* (3); *Microsporites* (1).

A remarkable similarity occurs between this assemblage and the one reported from Lower Carboniferous coals in northern Russia. Therefore a Lower Carboniferous flora is thought to be represented, but the majority of the species encountered have not previously been reported from the Mississippian of North America.

This floral similarity might perhaps indicate the presence of a continental facies of Lower Carboniferous strata between the Nahanni river and northern Russia, through the arctic. This assumption may be supported by the assumed Carboniferous coal deposits of the Parry Islands, and the Lower Carboniferous coals of Spitzbergen and Bear Island.

PETROGRAPHIC COMPONENTS AND STOKER COAL TESTING

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Petrographic analyses of stoker coals tested at Illinois Geological Survey have been resumed and preliminary results are given.

Polished surface techniques are used in present petrographic analyses. Vitrinite, exinite, inertinite and mineral matter were considered in the first of two series of analyses. In the second series a more detailed analysis was desirable; therefore vitrinite minus 24 microns, vitrinite plus 24 microns, exinite, resin rodlets, micrinite, semifusinite, fusinite and mineral matter were considered.

Data obtained show the relationship of petrographic components to combustion characteristics as outlined in the stoker tests; however the effect of the petrographic components are not equally indicated in all five combustion characteristics. These characteristics are uniformity of combustion, responsiveness, pickup, overrun, and heat obtained. Indications are that vitrinite has an effect upon uniformity of combustion and responsiveness but little on overrun and heat obtained.

Indications are that amount, occurrence and distribution of petrographic components within the coal affect the combustion characteristics. Effect of the vitrinite, which makes up the largest portion of the Illinois coals, appears to be modified by the amount of inertinite.

A comparison between chemical properties and petrographic components has been made. In this study a trend shows an increase in heat value with an increase in inertinite.

This is only a preliminary report, but results show that additional study is warranted.

[1] "A sample of coal from this area was collected by Mr. W. J. H. Patton, postgraduate student at the University of Alberta and submitted to the author by Dr. J. D. Campbell, Paleobotanist, Alberta Research Council, Edmonton, Alberta."

TURBIDITY CURRENTS FROM THE MAGDALENA RIVER, COLOMBIA

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The history of the Magdalena River of Colombia provides dramatic evidence that turbidity currents periodically form in fluvial sediments at the mouths of great rivers. On several occasions the destruction or sudden lowering of the Magdalena River mouth bar was followed by the breakage of a submarine cable which crosses the Magdalena submarine canyon in about 700 fathoms, about 15 miles seaward of the river mouth. In 25 years this cable broke 14 times in the vicinity of the canyon. The cable parted under great tension and on several occasions the cable was reported tightly wrapped with green grass. The periods of frequent cable breakage can be correlated with the progress of river improvement projects which caused the deepening of the bar. The turbidity currents probably ran the length of the Magdalena Submarine Canyon and out onto the Colombia Abyssal Plain where they deposited their load of sediments.

The characteristic occurrence of submarine canyons off contemporary as well as great Pleistocene rivers led to the suggestion that turbidity currents formed in the submarine fluvial deposits near these river mouths had eroded the associated submarine canyons. This evidence of modern turbidity currents formed by the destruction of the Magdalena River bar gives further proof of the turbidity current origin of submarine canyons and it demonstrates that river deltas are the temporary site of deposition of sediment which later travels further down the submarine slopes in the form of turbidity currents.

RESIDUAL SOILS OF THE WEST SLOPE OF THE SIERRA NEVADA AND THEIR ENGINEERING PROPERTIES

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The west slope of the Sierra Nevada is underlain by a basement complex of pre-Cretaceous metamorphic and granitic rocks with an average chemical and mineralogical composition of granodiorite and by Tertiary basaltic, andesitic and rhyolitic flows and sediments. The Foothills are underlain by middle Tertiary volcanic sediments, late Tertiary quartzose sands and bentonitic clays, Quaternary alluvial fans of arkosic sands and clays, and Recent stream deposits of arkosic sands and gravels.

Four major weathering cycles since Cretaceous time have left remnants of residual soils produced by the first three. The present cycle, dating from early Pleistocene and varying in temperature and rainfall from north to south and east to west and with time, has formed residual soils on all but the Recent deposits.

Residual soils on metamorphic rocks are usually thin, stony, clayey, plastic and impervious but lack stability. Granitic soils are usually deep, nonplastic and of high density and strength, but are relatively more pervious. Soils on Tertiary volcanics are variable but their properties average between those of metamorphic and granitic soils. Soils on late Tertiary and Quaternary sediments approach granitic soils in their characteristics but generally contain more clay and frequently develop hardpans or claypans.

MINERALOGY AND PETROLOGY OF THE MANGANESE PROTORE AT THE MERID MINE, MINAS GERAIS, BRAZIL

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The Merid Mine is located at Morra de Mina in the Lafaiete District of south-central Minas Gerais. The country rocks are a part of the Minas series and are Proterozoic in age. They consist of quartzites, greenschists, manganese carbonate-silicate rocks, manganese oxides, amphibolites, graphitic schists, and a variety of intrusives.

The results of field and laboratory studies indicate that the protores are metamorphosed sediments which originally probably consisted of banded manganese carbonates interlayered with cherts or mudstones. It is believed that virtually all of the manganese is derived from these sediments rather than from an igneous source.

The manganiferous sediments have undergone at least two stages of regional metamorphism resulting in rocks locally termed "carbonate- silicate" and essentially composed of spessartite and rhodochrosites; spessartite and quartz; or spessartite, rhodochrosites, and minor silicates. Accessories include graphite, pyrophanite, neotocite, bementite, thulite, manganoan apatite, and rare sulfides. The neotocite occurs as a decomposition product of rhodonite. Near the contact with the amphibolite the garnets are somewhat richer in iron and magnesium and a manganoan cummingtonite is found.

In proximity to the intrusives the protores show the effects of contact metamorphism. They contain little carbonate and are rich in tephroite and/or rhodonite in addition to spessartite. Hydrous silicates such as bementite and thulite are found locally, particularly near pegmatites. The occurrence in veins of massive rhodonite with spessartite and rare pyrite is attributed to processes of metamorphic differentiation probably abetted locally by hydrothermal activity related to the intrusion of the younger granite.

GEOLOGICAL PROBLEMS IN HIGHWAY ENGINEERING, MISSISSIPPI ALLUVIAL VALLEY OF LOUISIANA

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The major problems in highway construction in the lower Alluvial Valley of the Mississippi in Louisiana are (1) excessive settlement, (2) stability of foundations and embankments and (3) to provide an adequate subgrade for the pavement.

The soils in the alluvial valley which the highway engineers must use consist predominantly of Recent clays, silts, silty clays and fine silty sands. In many areas considerable organic material is mixed with the soil. In the Deltaic plain and coastal plains environment, the swamp and marsh areas often have deposits of mixtures of soft clays and organic matter called muck and mucky clays to depths of 10 to 30 feet. These mucks are extremely unstable and must be removed in order to construct stable embankments and roadways. The clays and silty clays of the Deltaic plain and backswamp areas in the Tensas and Boeuf basins are unstable and especially susceptible to excessive settlement.

Subgrade failures which result in excessive breaking and cracking of pavement are caused by these same unstable clays, silty clays and organic clays and silts.

Highway engineers have solved the problems presented by the unstable alluvial soils by scientific construction based on the results of geologic and engineering studies. It has been possible by the selection of materials, proper compaction and other scientific construction methods to build highways in the alluvial valley which will carry the modern high speed heavy traffic and stand up under the daily pounding of heavy vehicular loads.

FOUNDATION PROBLEMS DURING CONSTRUCTION OF ALGIERS LOCK AND CANAL

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Algiers Lock and Navigation Canal, built by the Corps of Engineers to provide an alternate connection between the Mississippi River and the Intracoastal Waterway, are located in an area underlain by Recent and Pleistocene soils typical of the New Orleans Area. Foundation problems common to the area were experienced while building structures along the canal. During excavation for construction of the lock it was necessary to reduce gas and hydrostatic pressures in underlying Recent sand stata and excavate very flat slopes to prevent unheaval of the bottom and failure of the slopes. Piles were used to transfer the weights of the structures through the Recent to less compressible Pleistocene stata in order to reduce settlement. Flow of gas from sand stratum through the piles required construction of outlet passages to prevent the gas from effecting the concrete above the piles.

Vertical sand drains extending to depths of 60 feet were used to accelerate consolidation of Recent clays beneath approach embankment and abutment areas of highway bridge crossing. Records of periodic measurements show the amount and rate of settlement which occurred, and comparison of borings made before and after construction of the approaches illustrates the change in water content which occurred in the foundation soils. Lateral movement of the bridge piers during construction was reported and investigation to ascertain their stability was made.

SCHEELITE IN FELDSPATHIZED GRANODIORITE, GABBS DISTRICT, NEVADA

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Economic quantities of scheelite occur in a sheared and feldspathized portion of the Illinois granodiorite stock, near Gabbs, Nevada. The granodiorite intrudes dolomite and shale of probable Upper Triassic age.

Both a westward projection of the stock and the adjacent sedimentary rocks were subjected to strong compressive forces during or shortly after the emplacement of the granodiorite. The dolomite is thrust over the granodiorite, and the latter is intensely sheared for several hundred feet from the contact. The scheelite mineralization is one stage of a metasomatic replacement process; the metasomatizing solutions were guided by the shear and fracture zones. The mineralogical changes effected are concentrated where crushing and fracturing were most intense, and particularly where there was recurrent crushing. Four successive stages of metasomatic alteration can be recognized:

1. Feldspathization, the dominant process being replacement of quartz by orthoclase and oligoclase.
2. Introduction of more plagioclase, accompanied by minerals such as garnet, diopside, and hastingsitic amphibole, forming "Ore-type" rocks.

3. Scheelite mineralization, essentially confined to those "Ore-type" rocks which have been subjected to later crushing.
4. Quartz veining.

In spite of the intense crushing no mylonitic rocks were observed, the feldspathized rocks are commonly coarse-grained, and low temperature minerals such as clay minerals and chlorite are generally absent. These features indicate a high temperature for the mineralization, which probably took place while the intrusion was still hot.

PEGMATITE MINERAL DEPOSITS OF THE ALTO LIGONHA AREA, PORTUGUESE EAST AFRICA

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Pegmatite bodies that contain columbite, beryl, lepidolite, bismuth and mica occur in the Alto Ligonha region of Portuguese East Africa. Pegmatites containing these economic minerals are restricted to belts of metamorphic schists while pegmatites in granitic rocks are barren.

Mining of columbite-bearing eluvial gravels derived from weathering of the pegmatites is economically feasible but exploitation of the pegmatites themselves has had limited success. A detailed study of the pegmatites was carried out to determine why pegmatite mining had proved uneconomic at depth and whether selective mining could bring about increased yields of the economic minerals. The internal structure of the bodies and the relationship of economic minerals to internal structure offer a solution to these questions.

The internal structure of the pegmatites is very similar to that of comparable bodies in many districts of the United States and Canada. The same mineralogical assemblages are present and these occur in the same sequence from walls inward. This is thought to be further support for the concept of origin by crystallization in a restricted system for the zoned pegmatites. Two zones within the pegmatites of the Alto Ligonha area appear to have formed partially by replacement, but this process has been of only minor importance in pegmatite genesis.

There seems to be a regional zoning of pegmatites in the area based on the presence or absence of lithium minerals. Pegmatites lacking lithium minerals have a simpler internal structure than lithium-bearing bodies.

GEOLOGICAL OBSERVATIONS FROM THE GENEVA CONFERENCE ON PEACEFUL USES OF ATOMIC ENERGY

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Some 1,100 papers were submitted to the United Nations' conference on the peaceful uses of atomic energy held at Geneva, Aug. 8–20, 1955. Among the papers submitted, ninety-five were especially prepared for the conference on the geological aspects of the natural occurrence of uranium and thorium. While the proceedings of the conference are to be published and may be in print by the time this abstract appears, several have suggested that a review of more salient features would be of interest to the Society.

Representatives of twelve delegations participated in a panel session on the natural occurrence of uranium and thorium. An opportunity was offered to compare occurrences in different areas on a world-wide basis. Strong emphasis was

placed on the conditions of emplacement in vein deposits both in the Belgian Congo and Canada. Important strides have been made in both areas in recent years in the interpretation of the conditions of vein formation. The interpretations of origin and factors involved in structural, mineralogical and depositional control applicable to the western United States uranium province drew a large part of the attention of the conference. Special attention was devoted to urano-organic types of accumulation. Another subject of general interest concerned the factors involved in the accumulation of detrital thorium deposits.

It is proposed to discuss the conference from the standpoint of contributions to the geology of uranium and thorium.

ROCK WEATHERING IN ENGINEERING GEOLOGY—PROBLEMS AND NEED FOR RESEARCH

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Weathering processes either weaken or enhance the engineering and physical properties of rock and soil; ultimate use of the material dictates the significance of this alteration. Conditions controlling the weathering processes and factors affecting the phenomena are widely discussed in the literature. However, the significance of weathering, particularly regarding the engineering and physical properties of rock and soil masses, has received attention that is inadequate in view of its importance.

Problems of rock and soil weathering invariably confront the geologist dealing with: excavation characteristics and classification; rebound expansion; tunnels; slope stabilization; adequate foundation, groutability, permeability and groundwater movement; reservoir leakage and silting; and selection of construction materials. To strengthen geological interpretation and "forecasts," further research investigations are needed on the principal types of rock and soil to establish criteria for: (1) determining the rate of weathering processes; (2) recognition of the degree to which weathering has progressed; (3) determining the engineering and physical properties of the material for each stage of alteration; and (4) applying the criteria to a weathered mass, and arriving at an appraisal of its engineering and physical properties.

If available, these data would aid planning and construction efficiency, reduce the "risk" inherent in dealing with weathered rock and soil, and eliminate many design changes often necessary after construction begins. Some research investigations along this line are currently underway.

TRACE ELEMENT EXPLORATION OF MAINE LAKE WATER

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Spectrographic determination of trace elements in lake waters was applied as a reconnaissance prospecting method to a remote area containing approximately 20,000 square miles in northern Maine. From this site, poorly prospected because of vegetation and a scarcity of outcrops and relatively free from water contamination caused by industry, 689 water samples from 467 lakes were analyzed.

Data for twelve elements normally present in trace amounts in natural waters—copper, lead, zinc, silver, tin, nickel, chromium, manganese, molybdenum, vanadium, zirconium and titanium—were evaluated by studying their variations from lake to lake. Use of element weight percentage concentrations in evaporated water residue

furnished data which were not affected by rates of erosion and changes in amounts of rainfall and runoff. All values for each element plotted on a base map of Maine revealed that often lakes with higher values formed groupings which represent localities of greater possibility for mineralization. The reliability of these groupings, or anomalies, has been established by correlation with geologic features and by confirmation with known mineralization. The distribution of the anomalies was expounded geochemically using pH data to account for the behavior of the elements in the weathering cycle. In south-central Piscataquis County one locality containing anomalies for eight elements was sampled in more detail. The result was that three limited zones, each of less than forty square miles, for lead, zinc, silver and copper mineralization were recommended for more specific studies such as soil analysis.

GEOLOGY OF URANIUM

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Igneous processes tend to concentrate uranium in late phase differentiates, notably in pegmatites, small alkalic plutons, and veins or other epigenetic deposits. The concentrations in igneous rocks are syngenetic. They may be large but are low-grade. Veins and other epigenetic deposits associated with igneous rocks are generally small, but some are high-grade. Weathering and sedimentary processes may either disperse or concentrate uranium, depending primarily on climate. Some primary uranium-bearing minerals accumulate in placers. Others are dissolved and the uranium is transported by ground and surface waters from which it may be precipiated in favorable receptors to form epigenetic deposits. Most deposits thus formed are low-grade but some are large. Some uranium in solution reaches the sea and may be extracted to form large, low-grade accumulations in phosphorites or black shales. Metamorphic processes may effect concentrations of uranium by converting pre-existing rocks to magma, which subsequently may form uranium-rich differentiates, or by "sweating" uranium out of weakly uraniferous rocks and concentrating it in favorable geologic settings.

Most of the world's important uranium deposits are clustered in a few areas of provinces that may represent uranium-rich portions of an originally inhomogeneous crust. These uranium-rich provinces apparently persist through long periods of geologic time. Within them, some types of uranium-rich rocks and uranium deposits may be relatively short lived, depending on the geologic history and climate, but as they are destroyed by erosion or metamorphism, others in equilibrium with the prevailing environment may form.

THE MOST IMPORTANT RESULTS OF MICROFLORA INVESTIGATIONS IN TERTIARY AND MESOZOIC STRATA OF EUROPE, ESPECIALLY OF GERMANY

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A close similarity has been shown between the microflora of Europe and North America in Tertiary age, and apparently in the Mesozoic too. Therefore, the experience in palynological work gained in Europe, especially in Germany, during the last twenty-five years may be helpful to American workers. The following paper is intended to give a summary of this experience.

Soon after 1930 when R. Potonie began the first serious investigations on the pollen and spores of German coals, he was able to divide the Tertiary of Middle Europe into three parts by the use of microflora. The extensive investigations performed later showed that the change of flora caused by evolution and extinction was very slight, at least since Middle Tertiary time; and plant migration caused by change in climate was very slow and gradual. Thus, we are unable, even today, to distinguish many more subdivisions than those designated by Potonie.

A good start has been made in recent years in stratigraphic investigations of Mesozoic beds but generally, in Europe, it is difficult to get good results because these beds contain in most cases only layers with a small spore content.

In spite of the generally slow change of floral development in the Tertiary it was possible to get good results in stratigraphic work by correlating formations, coal seams, and different layers of coal seams. For example, the coal seam from Niederhein which is normally 270 feet thick, can be divided into three main divisions with eight subdivisions with the help of spore diagnosis. These subdivisions are always recognizable in bore holes over an area of many miles. In a certain coal field at Morschenich, near Cologne, it was necessary to obtain a more detailed spore diagram. Here it was possible to divide the profile of the 180-foot-thick coal seam into 44 different horizons, and to trace these single horizons over several hundred yards.

These results become available only by an understanding of the recognizable microfloristic factors which indicate different fossil plant associations in different horizons of a coal seam.

In general, the nomenclature and taxonomy of the Tertiary pollen and spore flora are in a state of chaos. This would not be necessary if all authors had handled the names of the microfossils in accordance with the existing rules of the International Code of Botanical Nomenclature. The only possible way to resolve this chaos is to prove very carefully in the literature which names are valid and which are not. R. Potonie has been working a year on these troublesome problems. Besides names of species he has sampled about 400 names published in the literature for Mesozoic and Tertiary spore and pollen genera and other kinds of higher units of taxons. By April, 1955, he had worked over about 20 genera and with these he found that many of the names existing in the literature were weak when examined following the rules of principal type and priority.

THE FeS—NiS SYSTEM

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The binary system FeS—NiS has been studied as part of a detailed investigation of the sub-solidus phase relations in the ternary system Fe—Ni—S. The experiments were performed in evacuated, sealed silica-glass tubes. FeS has a hexagonal structure of the NiAs type. β-NiS with the millerite structure inverts at 396° C to α-NiS with the hexagonal NiAs structure. Above this inversion point, therefore, FeS and α-NiS are isostructural. FeS and NiS were found to form a complete solid solution series above 396° C. The solidus curve for the FeS—NiS system was determined. Homogeneous mix-crystal formation from the FeS and NiS end members required three months at 500° C. The unit cell dimensions were determined for these solid solutions across the entire system at this temperature.

The α-β transition temperature for mix-crystals on the NiS side of the system decreases sharply with increasing iron content. For example, α-mix-crystals containing 10 wt. % FeS were found to be stable at temperatures as low as 300° C.

Earlier investigators reported pentlandite in the FeS—NiS system. The present study demonstrated that the pentlandite structure does not occur. This structure requires a metal to sulfur ratio of 9:8 and, therefore, the pentlandite reported earlier was probably due to loss of sulfur.

PERMAFROST NEAR LAKE ATHABASKA, SASKATCHEWAN

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Engineering operations in the Beaverlodge area on the north shore of Lake Athabaska, Saskatchewan, related to the uranium mines, have disclosed sporadic permafrost. Maximum depth of frozen ground appears to be about 25 feet so that this location must be close to the southern boundary of permafrost at this longitude. The usual phenomena are observed when the vegetal-cover over the permafrost is disturbed. Sharp-faced boulder-sized holes are found in the frozen silt the origin of which is thought to be the melting of small blocks of ground ice. Observations of soil temperature variations in this area confirm the probability of local ground ice, the melting of which is discussed in relation to ice-melt depressions in general. The observations recorded are part of a continuing survey of the southern boundary of permafrost in Canada being carried out by the Division of Building Research of the (Canadian) National Research Council.

INTERRELATION OF RIVER CHANNEL PATTERNS—BRAIDED, MEANDERING, AND STRAIGHT

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Natural channels characteristically exhibit alternating deep and shallow sections called pools and riffles. This alternation occurs in all channel patterns whether meandering, braided, or straight. The length of the pool or distance between successive riffles in a straight channel equals the straight line distance between successive points of inflection in a meandering river of the same discharge. The shallow sections in a meander correspond to riffles in the straight channel.

The distance between riffles, equal to half the wave length of the meander, is shown to vary as a linear function of channel width. The meander wave length is approximately 10 times the channel width regardless of the size of the river.

Meandering and braided streams respectively have characteristic combinations of values of slope and bankfull discharge. At a given discharge, a change from meandering to braided is accompanied by increase of slope. At a given slope, braided channels are associated with a greater discharge than meandering ones.

The hydraulic characteristics of channels of different patterns exhibit a spectrum or continuum within which braided, meandering, and straight channels intergrade.

ALTERATION NEAR AN ACID HALOGEN-SULFUR FUMAROLE

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A series of specimens of ash and pumice, collected outward from the throat of Fumarole No. 1 of Zies in the Valley of Ten Thousand Smokes in 1952, has been analyzed for major and minor constituents. The bulk density—approximately 0.80 for unaltered ash—was determined from weighing blocks of known volume, and chemical addition or subtraction was calculated for unit volumes. Early subtractive alteration is somewhat masked by later addition of material. Both silica and alumina have been added in substantial amounts near the fumarole throat, but it is evident that silica was leached in an early stage of alteration and alumina probably

was leached at depth and redeposited near the surface. Iron, sodium, and potassium were leached near the throat and redeposited a short distance away, but calcium and magnesium may not have been much affected. Appreciable quantities of several minor elements have been added, with maximum concentrations at distances from the throat that range from 1 inch for Pb, Zn, and Cu, to about 4 feet for Ni, Co, and Se, with the maximum for Sb, As, Y, and B in intermediate positions. Fluorine, chlorine, sulfur, and phosphorus were added near the throat, and no CO_2 was added to the ash by the fumarolic alteration. Goethite, hydromica, montmorillonite, kaolinite, and opal are the chief alteration minerals observed.

The alteration is similar to that produced by strong sulfur acids in fumaroles and elsewhere, but there is perhaps greater transportation of silica and lesser movement of calcium and magnesium.

FOUNDATION CHARACTERISTICS OF LATE QUATERNARY CLAYS OFFSHORE NEAR MODERN MISSISSIPPI DELTA

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Studies at oil well drilling sites in the Gulf of Mexico have revealed shear strength variations from 2,000 pounds per square foot to less than 16 pounds per square foot for soils at the mudline. Penetration of bearing piles supporting existing structures varies from 15 to 380 feet below the mudline. Delineation of such variations, by areas, would be desirable. To accomplish this, scarce boring information must be extended by geologic interpretation.

Strength of water-deposited clays varies directly with pre-consolidation pressure (the highest inter-granular pressure which the soil has experienced). Pre-consolidation pressure can be less than the total submerged weight of overlying soil (when overburden includes very young deposits) and sometimes more than overburden weight (if erosion has occurred). Test data indicate a ratio of shear strength to pre-consolidation pressure of 0.15 for Recent pro-delta deposits of the Mississippi River.

Study of strength versus depth profiles at various offshore points near the modern Mississippi delta indicates: (1) deposition near mouth of Southwest Pass is so recent that pre-consolidation pressures and soil strengths are negligible to 140-foot depth; (2) clay deposits 10 miles offshore southwest of Venice are normally consolidated, verifying greater age of these deposits relative to those last mentioned; and (3) erosion has removed 30 feet of soil in Bay Marchand area. Similar strength patterns should exist in areas where clays of comparable age were deposited in comparable environments, as revealed by geologic studies of delta formation.

CARBONATE BANK DEPOSITS IN THE DEVONIAN OF THE ALBERTA ROCKY MOUNTAINS [1]

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The upper part of the Upper Devonian Fairholme group in areas of carbonate development in the Alberta Rockies consists of a complex of limestones and dolomites. Among these, grey and light grey massive and thick bedded rocks, feature-

[1] Published by permission of the Acting Deputy Minister, Department of Mines and Technical Surveys, Ottawa, Canada.

less in the field, show interesting variation in thin section. In the limestones four main lithologic types are recognized: (1) "cabbage-head" stromatolites and irregularly banded rocks, commonly occurring as bioherms, formed of interbanded, recrystallized and aphanitic limestone commonly with grumelous or "clotted" texture; (2) bioclastics formed of fragments of corals, stromatoporoids, brachiopods and molluscs, from pebble to silt grade particle size, in clear calcite matrix; (3) medium to coarse grained granular rocks formed of rounded to subrounded grains of aphanitic limestone in clear calcite matrix; (4) grumelous or "clotted" textured rocks exhibiting incipient granularity of aphanitic limestone, but without discrete grains. All possible integradations occur. Calcispheres are common in types 2, 3 and 4. All types may be dolomitized but structures are preserved as pleochroic shadows independent of the crystal grains of dolomite.

The macro-structure of type 1 may be matched by recent laminated sediments trapped by blue-green algae on emergent mud flats in Florida Bay; of type 2 by beach and shallow water sands near the fringing Cays of the Bahama Banks; of type 3 by underwater dune sands from the interior of the Bahama Banks as described by Illing. Type 4 is uncertain in origin but is believed to be formed from flocculant muds possibly algal in part

WRENCH FAULT MECHANICS

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Extending the work of Anderson, Hubbert, and Hafner on faulting, the authors develop the hypothesis that anticlinal folds, thrust faults, and *wrench faults* can be generated as a result of movement on a large wrench fault such as the San Andreas of California. Extension of this concept leads to the conclusion that for any given tectonic area, eight directions of wrench faulting and four directions of anticlinal folding and/or thrusting should accommodate the structural elements of that region; these directions should have a more or less symmetrical disposition relative to the direction of the primary compressive stress. The angles α, β, and ν are defined so as to describe the geometry of such a *wrench fault tectonic system* relatively completely.

The authors' interpretations of tectonics in various areas indicate that wrench fault tectonic systems do exist in nature, and in fact are aligned systematically over large portions of the earth's crust as indicated by Hobbs, Vening Meinesz, Sonder, and others. On the strength of this, eight principal wrench directions are defined in terms of major elements of the earth's crust such as the Alpine fault of New Zealand. Structural elements aligned in these eight directions constitute major features of the *regmatic shear pattern* of Sonder. The authors conclude that the shear pattern results from stresses which are oriented essentially meridionally, and which have been acting in nearly the same direction throughout much of crustal history.

It is concluded that major wrench faults, which penetrate the entire outer crust of the earth and which result in wholesale segmentation of the outer crust into polygonal blocks, constitute the primary type of yielding in the crust.

Possible origins of the stresses involved, formation of geosynclines, island arcs, volcanism, crustal evolution, etc., are discussed in terms of these ideas. Some possible objections and weak points in the argument are pointed out, and suggestions for further study are included.

ENGINEERING GEOLOGY OF THE THARTAR PROJECT (IRAQ)

JOHN O. NIGRA

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Limiting the flood discharge of the Tigris and diverting excess water along a terraced-earth channelway into the Thartar depression are objectives of a significant Iraqi project. The depression represents the widening of Wadi Thartar at latitude 34° N into a large, ephemerally dry salt-lake about 40,000 acres in extent with an elevation ten feet below sea-level at its center. The origin of this feature, much disputed, is believed chiefly attributable to solution subsidence in flat, underlying carbonate and evaporite beds rather than to downfaulting or wind erosion.

Difference of geological opinion also exists as to whether or not this natural reservoir lying between two extensive river valleys is water-tight. Although the base-levels of the Euphrates and Tigris are above the bottom of the sink, which is separated from the twin rivers by the high ground of the Jezirah desert, seepage appears to be precluded by a hydraulic gradient sloping less than the shallow regional east dips of the subjacent Euphrates (lower Miocene) reef limestone and Lower Fars (upper Miocene) marine limestone, anhydrite and gypsum with alternating impervious beds of shale.

The Thartar basin is expected to hold 68 billion cubic meters of water within 870 square miles when filled to the plus 200-foot contour, the critical level above which seepage can easily occur into aquiferous Bakhtiari (Pliocene) conglomerate seen in outcrop on the eastern embankment to overlie Upper Fars non-marine soft clays and marls. The impounded water may become somewhat saline but will be useful for irrigation.

COMPUTATION OF CHEMICAL ANALYSES OF COAL SPEEDED BY USE OF IBM PUNCHED CARDS

MARGARET A. PARKER *

Illinois State Geological Survey

The recording of chemical analyses on punched cards facilitates the integration of chemical data with geological data for mines and drill holes. The punched cards may be used to prepare copy for offset printing and reduce costs of publishing the analyses.

The results of the chemical analysis of coal are punched into cards for computation by electronic machine to obtain proximate and ultimate analyses of coal on air dried, as received, moisture free, moisture and ash free, dry unit coal, and moist unit coal bases. Calorific and B.t.u. values can also be obtained. Because of the speed of the electronic calculating machines, about 100 analyses are normally the minimum that can be calculated at one time.

Where the number of analyses is not sufficient to warrant the use of electronic calculating machines, the analyses can be punched directly into cards, crossfiled, and used for publication.

The proposed method for handling chemical analyses is the result of work at the Illinois State Geological Survey, the University of Sydney, and the Joint Coal Board, Sydney, Australia. The work at the latter institutions was done under a Fulbright research grant.

* Presented with permission of the Chief, Illinois State Geological Survey.

PETROGRAPHY AND REGIONAL CHARACTERISTICS OF THE LOWER KITTANNING COAL

NORMAN SCHAPIRO AND AUREAL T. CROSS
West Virginia University and West Virginia Geological Survey, Morgantown, W. Va.

Polished surface preparations of complete channels of twenty-one samples of Lower Kittanning coal from West Virginia, Ohio and Pennsylvania have been examined under low magnification and the results compared with studies of five of these coals examined under high magnification by both transmitted and reflected light.

A detailed comparison was made between results of continuous-transect and point-count methods of recording total constituent particles. A study to determine the reliability, quality of representation and utility of analyses of selected slides or units as compared with complete columns showed comparable representation. The results demonstrate the point-count method to be reliable, to be faster and to have greater accuracy and utility in tabulating finer sized constituents.

A simplified composite classification of coal components and constituents was devised in which several size units are recognized for some constituents. This allows the uniform recording of petrographic units by either reflected or transmitted light techniques, and regrouping these data for comparison with those from studies using different classifications or methods. This also makes it possible to tabulate the amounts of various size fractions of ingredients in various ways for utilization in coal beneficiation. There is considerable latitude in the character of the components themselves and legislated definitions of these are not acceptable.

No evident relationship of bright to dull or cannel coal to regional position is evident based on petrographic evaluation. There is an expectable change in quality of anthraxylon and translucent attritus to the east associated with increase in rank. Local influences on petrographic composition are more important.

CONCEPT, TECHNIQUE, AND LANGUAGE IN COAL PETROLOGY

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U. S. Geological Survey, Columbus, Ohio

Ideas, methods, and expression are closely interrelated in any field of science during its period of rapid growth. In development of coal geology all phases are evolving together and the stability of basic concept that characterizes long established disciplines is not conspicuous in this field. For example, the parameters of *type, rank* and *grade* variation in coal, concepts that are fundamental to organization of modern information about this singular class of rocks, are still incapable of a precise definition. The technical meaning now attached to these terms has evolved almost entirely within our own lifetimes.

The *techniques of differentiation* seem as essential as *ideas about differentiation* for determination of types of coal. From about 1920 to 1930 ideas apparently outstripped development of differentiative methods. The original ideas were not sufficiently explicit with regard to method, and this has served as a source of confusion and continuing difficulty in expression. Controversy about coal petrologic terms is a symptom of poorly defined methodology, rather than the result of an essential conflict in concept.

Quantitative methods for micro-differentiation of coal were applied by R. Thiessen in 1931. A practical method, generalized in some particulars, was devised first. Recently we have developed a more explicit method of component analysis. This method provides a means for detailed quantitative integration of

the different types of coal. It can serve as a common basis for expressing differences between the various systems of routine analytic coal microscopy. It should enable us to better evaluate the variations of petrologic composition and texture that denote differences in type and to relate these variations to rank and grade for purposes of scientific classification.

GEOLOGICAL PROBLEMS IN THE DESIGN AND CONSTRUCTION OF FLOOD CONTROL STRUCTURES IN THE MISSISSIPPI ALLUVIAL VALLEY

JOHN R. SCHULTZ

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Nearly all geological problems connected with design and construction of flood control structures (levees, earth dams, outlet structures, and drainage channels) in the Mississippi alluvial valley are related to the existence of a sand and gravel substratum and a fine-grained topstratum of highly variable thickness. The substratum affords the best foundation for heavy structures, but is highly permeable and careful dewatering is necessary in excavations that penetrate any considerable thickness of the topstratum. Major irregularities in thickness of the topstratum, clay plugs for example, also have considerable influence on localization of seepage under levees and other water barriers. Distribution of discontinuities in the topstratum, orientation of clay-filled swales for example, is, therefore, a major consideration in the location of water barriers as well as the governing factor in the spacing of relief wells or other devices designed to alleviate uplift pressures caused by underseepage.

Clay plugs, or other thick deposits of cohesive materials, are more resistant to erosion by the river than sands and other more or less cohesionless materials and tend greatly to retard bank recession. Thick deposits of cohesive materials may also have an important influence on the future direction of bank migration. Consequently, an analysis of bank stability and probable future trends of bank migration is an important factor in selecting locations for large permanent structures.

STRATIGRAPHIC PATTERN IN PRE-MARMATON DESMOINESIAN CYCLES [1]

WALTER V. SEARIGHT

At least 18 coal-bearing cyclic successions are recognized in strata of pre-Marmaton Desmoinesian age in Missouri, Kansas, and Oklahoma. Each is composed of lithologic units arranged in definite stratigraphic order. Many contain in addition faunal units which likewise follow a stratigraphic pattern within the succession, but individual successions include only part of the characteristic units. The lithologic units differentiated within a cycle from bottom to top include the following: 1) mottled, noncalcareous shale, 2) calcareous shale or dark earthy limestone containing many small productids or bryozoa, 3) gray shale, 4) calcareous shale or earthy limestone containing molluscs, 5) mudstone or dark shale with siderite concretions, 6) a ledge of massive gray limestone, 7) black fissile shale with phosphatic concretions, 8) fossiliferous limestone with fusulinids, 9) shale with siderite concretions, 10) sandstone, commonly micaceous, grading upward into micaceous sandy shale or stigmarian sandstone, 11) hackly, earthy underlimestone, 12) underclay, 13) coal. The stratigraphic order is determined from individual

[1] Presented with permission of the State Geologist of Missouri.

cyclic successions although only a few units are present in each. If a composite cyclic succession be made from all the units recognized, the order from the next lower coal is that given. This "complete" or composite succession has an order or pattern very similar to the megacyclothem of Moore.

VARIATION OF COAL REFLECTANCE *

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Several thousand measurements of coal reflectance were made to study the variation of reflectance with rank, variation within and between vitrain bands, and variation related to the wave-length of the incident light. Measurements were made of small areas of polished coal blocks under a metallurgical microscope using an electronic photometer (with photomultiplier) which permits a reproducible, objective estimate of the reflectance. The coals sampled varied from high volatile C upward through the entire range of bituminous coals and anthracites to meta-anthracite and "graphitized" coal. Statistical methods were used to insure correct sampling design and proper analysis of results.

The reflectance measurements indicate that horizontal variation (parallel to banding) is negligible. In some bands vertical variation (normal to banding) is statistically significant; the central portions of the bands are slightly higher than the borders. In many coals there is significant variation between vitrain bands. The range of variation between bands narrows with increasing rank to a minimum in the low volatile coals. The variation between bands in any sample is not as great as that between coals of high and medium volatile, medium and low volatile, and low volatile and anthracite rank. In some bands abnormal reflectance values may be due to the effects of included resinous material or to slight fusainization of vitrinite.

Increase in reflectance with rank is pronounced, as has been pointed out in the past, but present data indicate a gradual, transitional increase rather than a discontinuous, stepwise progression.

PARAGENESIS AND STRUCTURE OF PITCHBLENDE-BEARING VEINS, CENTRAL CITY DISTRICT, GILPIN COUNTY, COLORADO

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U. S. Geological Survey, Denver, Colorado

Substantial quantities of pitchblende have been produced from early Tertiary gold-, silver-, and sulfide-bearing quartz veins in the Central City district, within the mineral belt of the Front Range. The veins cut a complex mass of metasedimentary, metasomatic, and igneous rocks of Precambrian age and hypabyssal intrusive rocks of early Tertiary age. They are fissure fillings that formed at intermediate temperatures and pressures. Vein-filling took place during three stages of mineralization.

The veins consist chiefly of quartz. Pyrite, sphalerite and galena are the principal metallic minerals and tennantite, chalcopyrite, enargite, and pitchblende are less abundant. The pitchblende typically is hard and lustrous and characteristically has a colloform texture; locally it is soft and sooty. The pitchblende contains

* Published with the permission of the Chief, Illinois Geological Survey.

unusual quantities of zirconia and molybdenum. Pitchblende, the first metallic mineral to form was deposited contemporaneously with quartz, and was followed by pyrite, sphalerite, copper-bearing minerals, and galena. Fracturing and vein reopening took place after pitchblende and after pyrite deposition.

Pitchblende is present in only a few veins. It occurs locally along three of the five principal vein sets, in ore shoots or small lenses and pods that are separated by vein material essentially barren of uranium. The known ore shoots are small, the largest being about 50 feet high, 20 feet long, and an average of a foot wide. Some of the shoots are systematically arranged within the veins but others are erratically distributed.

*UTILIZATION OF BUSINESS MACHINE TABULATIONS FOR THE SYSTEMATIC CLASSIFICATION OF GEOLOGIC DATA**

WILLIAM H. SMITH AND RUSSELL A. BRANT

Ohio Division of Geological Survey, Columbus, Ohio

In recent years two methods of punched card cataloguing of geologic data have come into use. One utilizes the Keysort card which is usually punched and sorted by hand and the other the business machine card, which is punched and sorted mechanically and the data listed on form paper from type bars actuated by the punched card.

A system employing the use of business machines has been developed at the Ohio Geologic Survey in connection with coal resources studies. It provides a systematically organized summary and index of large volumes of geologic data which facilitates the mapping of economically or stratigraphically important strata and evaluation of mineral and fuel reserves.

The system utilizes number and letter symbols to classify the numerous items of geologic data and provides a convenient, time-saving device for making readily available the information essential in preparing reports concerning areal mapping, stratigraphic summaries, coal resources, and county or regional studies.

The various geologic, location, and identification data are coded by the geologist directly onto the stratigraphic record. The system of codes devised employs a primary code for stratigraphic position, and a series of secondary codes to classify items of geologic significance regarding the key bed at a given locality together with thickness, sequence, and character of sediments in the interval upward to the next younger key bed. The coded information is then punched onto cards from which it may be sorted and listed mechanically in any arrangement convenient to the problem at hand.

MINOR ELEMENTS IN THE ASH OF COALS FROM WESTERN KENTUCKY, INDIANA, AND ILLINOIS

TAISIA STADNICHENKO, PETER ZUBOVIC, AND ELIZABETH L. HUFSCHMIDT

U. S. Geological Survey, Washington 25, D. C.

Ash samples of more than 1,000 blocks from over 60 columnar coal samples, from western Kentucky, Indiana, and Illinois, were analyzed for Ge by semiquantitative methods, mostly with phenylfluorone. An additional 14 elements (Be, B, Ti, V, Cr, Co, Ni, Mo, Cu, Zn, Ga, Sn, Y, and La) were determined spectrochemically in 250 selected blocks or in special coal samples with recognizable plant

* Presented with permission of the Chief of the Division of Geological Survey, Ohio Department of Natural Resources.

structures. The results of the analyses, presented in tables, are correlated with sedimentary characteristics of the coal samples or with the outstanding features of the plants which formed them.

Good Ge mineralization (0.1 to 0.26 percent) has been found in the ash of coal from several beds in various localities of these States. Very large Zn (as much as 10 percent) concentration in sedimentary ash was found in the northern part of Illinois and Indiana. The ash of several block samples contained high V (up to 4.2 percent), Cr (up to 1.2 percent), Mo (up to 0.15 percent), and Be (0.03 percent) content.

THE MINERALOGY OF THE PEANUT MINE, MONTROSE COUNTY, COLORADO

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The vanadium-uranium ore in the Peanut mine, Bull Canyon mining district, Montrose County, Colo., occurs in the Salt Wash sandstones member of the Morrison formation of Late Jurassic age. The ore bodies are relatively small, but grouped in clusters, and are enclosed in the upper parts of festoon cross-lamination structures. The festoon surfaces are relatively impermeable to ground water, and small perched water tables saturate most of the ore bodies.

Most of the ore is unoxidized because oxidation has been inhibited by stagnant ground water of the perched water tables. The parts of the ore bodies above the water table show a vertical zoning of oxidation products; the upper parts are the most oxidized.

Primary ore minerals are uraninite, coffinite, montroseite, and vanadiferous clays. The first oxidation products of the primary ore are paramontroseite and three new vanadium (IV) minerals. Melanovanadite, two new vanadyl vanadates, and corvusite are formed next. Tyuyamunite and pascoite are the only highly oxidized minerals found in the deposit.

Metallic minerals associated with the ore are marcasite, pyrite, chacopyrite, chalcocite, digenite, galena, sphalerite, molybdenite, and native selenium.

Barite, pyrite, and montroseite commonly occur together with coalified wood. Limonite and malachite and a possible calcium selenate are associated with the oxidized parts of ore bodies.

ENGINEERING PROBLEMS ASSOCIATED WITH WEATHERED LIMESTONE

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The difficulties associated with the design and construction of dams and reservoirs in areas of cavernous limestone rocks have become generally known through publications of the TVA. However, other types of engineering problems associated with weathered limestone are not as well recognized.

Of primary concern in the construction of highways, airfields, foundations of light structures, or tunnels are the engineering properties of the residual soil and the character of the contact between the soil and the limestone. On the other hand, the presence of solution cavities and the properties of their fillings are of importance in the design and construction of heavy structures.

A summary of physical soil constants including Atterberg limits, natural water contents, compaction data and textural classification are given for typical limestone

soils in central United States and Puerto Rico. These data have been obtained primarily from various highway organizations. The clay mineralogy and activity have been determined for representative samples. Highway performance can be correlated with these soil properties.

Test pits sunk during preliminary exploration for a tunnel at Chattanooga, Tennessee, penetrated as much a 25 ft. of residual soil developed over Chicamauga limestone and Knox dolomite without encountering sound rock. Physical soil constants and strength characteristics of the residuum are shown.

Case histories of building foundation problems in areas of weathered limestone in Iowa, Illinois, and Puerto Rico are discussed.

MINERALOGY AND GEOCHEMISTRY OF THE URANIUM DEPOSITS IN THE WHITE CANYON AREA, SAN JUAN COUNTY, UTAH

ALBERT F. TRITES, JR.

U. S. Geological Survey, Denver Federal Center, Denver, Colorado

Uranium deposits in the White Canyon area, San Juan County, Utah, occur in channels that have been cut into beds of the Moenkopi formation of Early Triassic age and that have been filled by sediments of the Shinarump conglomerate of Late Triassic age. The most favorable beds are sandstone and conglomerate that are interbedded with siltstone and that contain abundant carbonized wood and clay seams.

The ore deposits are generally classified as the copper-uranium type and contain pyrite, chalcopyrite, uraninite, bornite, sphalerite, and galena, listed in order of abundance. Uraninite, pyrite, and bornite have been deposited principally as replacement of organic material, chalcopyrite as disseminations in sandstone and replacement of wood, sphalerite as fillings of fractures, and galena as fillings of cavities. Uranium, copper, iron, arsenic, barium, cobalt, molybdenum, nickel, lead, zinc, and magnesium apparently have been added to the Shinarump conglomerate by the mineralizing solutions.

Oxidation of the ore bodies exposed at the rim of Shinarump conglomerate has produced an oxide zone which grades through a transition zone into the sulfide ore. Uranium, copper, and possibly iron have been secondarily enriched by solution in the oxidized zone and inward movement and redeposition in the transition and sulfide zones. The secondary uranium and iron have migrated farther inward than the copper and have been deposited as sooty pitchblende and marcasite, respectively. The copper has been concentrated as the supergene sulfide minerals chalcocite and covellite, and as hydrous sulfates and carbonates.

WALL-ROCK ALTERATION AS A GUIDE TO CARNOTITE DEPOSITS AND THEIR ORIGIN, NORTHERN BLACK HILLS, SOUTH DAKOTA

R. C. VICKERS

U. S. Geological Survey, University of Wisconsin, Madison, Wis.

Several carnotite deposits are present in the Fall River sandstone of Lower Cretaceous age on the north flank of the Black Hills, Butte County, S. Dak. The deposits are in a fine-grained, well sorted, persistent basal sandstone unit that ranges in thickness from 2 to 18 feet and dips about 4° NE.

Detailed mapping of the basal sandstone shows that all the known carnotite deposits and most of the areas of high radioactivity occur where the color of the

sandstone changes from reddish on the up-dip side to normal yellowish-gray or buff down dip. Radioactivity measurements in the field show that uranium is concentrated continuously along the sinuous red to buff contact for a known distance of at least 5 miles. Laboratory work indicates that the red color is not a function of the total iron present but is probably due to the alteration of hydrous ferric oxides of hematite.

The close association between uranium deposits and the red to buff color contact suggests that the two were formed by the same solutions. If so, the uranium was probably deposited from ground water that moved down dip and changed in character from oxidizing to mildly reducing. Concentrations of uranium have resulted from the localization of reducing conditions, caused perhaps by structures superimposed on the regional dip, local thinning or decrease in permeability of the sandstone, or concentrations of carbonaceous material.

OXIDATION OF THE COLORADO PLATEAU ORES AND ITS RELATION TO RECENT GEOLOGIC HISTORY

ALICE D. WEEKS

U. S. Geological Survey, Washington 25, D. C.

Oxidation studies are helping to clarify the problem of origin of the Colorado Plateau uranium deposits by eliminating from consideration those features formed during oxidation and the modifications made by recent ground water.

Geologic, mineralogic, and chemical evidence indicates that the carnotite ores on the Plateau have been derived by progressive oxidation of primary, black ores. The classification of Plateau ores on the basis of whether vanadium is associated with the uranium is important because during oxidation vanadium complexes all available uranium and effectively holds it in carnotite, a stable, secondary mineral. This permits the accumulation of large oxidized vanadiferous deposits at shallow depth. Only in the caliche zone at or close to the surface of the ground is carnotite being leached. In the absence of vanadium, unstable oxidized products such as uranyl carbonates and sulfates develop around uraninite. These are removed soon after they form, thus reducing the possibility of large, oxidized, nonvanadiferous deposits in the Plateau. In exploration for nonvanadiferous ores, one should consider conditions favorable for ore preservation along with other factors of favorability.

No significant secondary enrichment occurs in vanadiferous uranium ores. Only in a few nonvanadiferous uranium deposits that have a high sulfide content is secondary enrichment probably important.

The degree and depth of oxidation is related to the lowering of the water table following canyon cutting in the present erosion cycle and to the different capacities of the lenticular sands and clays to retain pore water above the regional water table.

ON THE URANIUM MINERALIZATION IN THE CAL URANIUM AND HOMESTAKE MINES, BIG INDIAN WASH, UTAH

GEORGE C. WITTER, JR. AND HEINRICH D. HOLLAND

Department of Geology, Princeton University, Princeton, N. J.

In the Cal Uranium and Homestake mines located in Big Indian Wash, southeast of Moab, Utah, uranium mineralization occurs in the basal member of the Chinle formation. Forty thin sections of samples of ore from these mines were covered with alpha-sensitive stripping film, and the distribution of radioactive centers was studied in relation to the mineralogy of the ore and of the ore bearing horizon.

The basal Chinle in Big Indian Wash consists of lenses of conglomerate, sandstone, siltstone, mudstone, and limestone. Calcite is present throughout the horizon and is believed to have been deposited as detrital grains. Pyrite is the most abundant sulfide present. Barite, detected in some of the thin sections, was found to replace quartz grains and always contains small, highly radioactive inclusions distributed along cleavage planes and grain boundaries. On the basis of X-ray studies it was concluded that the major portion of the uranium occurs in coffinite, usually as very small grains often associated with carbonaceous material along boundaries of grains of non-ore minerals.

STRESS–STRAIN RELATIONSHIPS FOR IGNEOUS ROCKS

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Excellent correlations are established between texture, structure and composition of igneous rocks and unconfined compressive strength, triaxial strength, Young's modulus of elasticity, and Poisson's ratio.

Strength and elasticity increase as quartz decreases in amount and plagioclase and/or ferromagnesian minerals become more abundant; however, the increase is attributed mainly to better interlocking and articulation of the crystals. Characteristic strength and elasticity are as follows for unaltered or slightly altered rock (length/breadth = 2):

Rock type	Compressive strength, psi × 10^3	Secant modulus of elasticity, psi × 10^6
Granites	20–35	4– 7
Syenites, Monzonites	35–50	7–10
Diorites, Gabbros	45–60	10–13
Glassy Volcanics	6–22	4– 8
Andesites, Basalts	25–50	8–12
Diabases	45–80	12–17

Porphyritic texture produces slightly higher strength but the elasticity is similar to that of non-porphyritic equivalents. Type and degree of alteration, fabric discontinuities, porosity, vesicularity, degree of fracturing, and seam fillings affect strength and elasticity in characteristic ways. Equal alteration, especially in feldspars, lowers strength and elasticity proportionately for all rock types. Under triaxial conditions rupture load increases linearly with lateral pressures up to 6,000 psi and a characteristic slope is obtained for each rock type. The relationship is retained, although at lower strength values, for equivalent altered rock. Poisson's ratio remains nearly constant for unaltered rock as axial stress is increased to 5,000 psi whereas for similar but altered rock Poisson's ratio is smaller, especially at low axial stress loads, but generally increases as axial stress is increased.

TECHNIQUES AND GUIDES FOR EXPLORATION OF URANIUM–BEARING SHINARUMP CHANNELS ON THE COLORADO PLATEAU

H. B. WOOD AND W. DAVID GRUNDY

Atomic Energy Commission, Grand Junction, Colorado

Detailed studies were made by the Commission of three areas on the Colorado Plateau in which uranium ore occurs in the late Triassic Shinarump conglomerate:

Circle Cliffs and White Canyon regions of southeastern Utah, and Monument Valley region of Utah and Arizona.

The following ore guides are suggested: (1) uranium ore is confined to the bottoms and sides of paleochannels and scours; (2) ore is most likely to occur in a poorly sorted, porous, argillaceous, arkosic sandstone and/or conglomerate interbedded with mudstone lenses and clay galls; (3) irregular channels with deep and narrow cross-sections and with variations in depth of scour are favorable for the occurrence of this type of lithology; (4) the presence of carbonaceous material and some clay lenses is important for uranium precipitation or concentration; (5) an appreciable thickening of the zone of bleaching in the underlying Moenkopi; (6) the nearby presence of copper sulfides, sulfates and carbonates; iron sulfides, sulfates and hydrous oxides; and cobalt arsenate.

In exploration for ore deposits it is recommended that the initial dip of the beds be reconstructed and that the pre-Shinarump topography be shown by contours indicating the shape and trend of the paleochannel. Then the projected trend of the channel is traced by drilling using fence and single hole patterns. If the paleotopographic contours are extended ahead of the drilling, few holes will be wasted and drilling will be confined to channels.

SCIENTIFIC NOTES AND NEWS

WILLIAM BENSON has left the U. S. Geological Survey to investigate uranium in North Dakota.

LOUIS KOENIG is now vice president of Southwest Reseach Institute, San Antonio, Texas, and will direct the expanded chemistry, chemical engineering, minerals, metals, high energy, and applied biology divisions.

DIONYS BURGER has resigned from the Tasmanian Geological Survey and is geologist to the Australasian Oil Exploration Ltd., Uranium Div., South Australia.

EVERETT GRAFF, consulting geologist and representative in Peru of World Mining Consultants, Inc., recently returned to Lima from Bolivia where he examined some nickel properties between Oruro and Cochabamba for a Chicago, Ill., group.

JOHN PAYNE, JR., with American Metal Co. since 1940, has been elected a vice president in charge of mining and exploration.

E. A. NOBLE has recently become a geologist with the AEC in Grand Junction, Colo.

W. B. G. WALKER, formerly with Bear Creek Mining Co., has been named geologist, Utah Copper division, Kennecott Copper Corp.

GEORGE S. HUME, Director General of Scientific Services, Department of Mines and Technical Surveys, has been elected President of the Royal Society of Canada for 1955–56.

HANS P. RECHENBERG has resigned as assistant professor of Mining Geology, Technical University, West-Berlin, and is now geologist with the Türk Maadin Sirketi Company, Istanbul, Turkey.

D. T. MITCHELL, assistant general manager, and A. BLATCHFORD, chief geologist, Emperor Gold Mining Company, Ltd., Vatukoula, Fiji, have been touring the United States and Canada. They have been studying methods and equipment and various mining operations in the two countries.

A. L. GRABOWSKY, mining geologist, Coporacíon Minera de Bolivia, La Paz, Bolivia, is mine superintendent of the Calpa gold mine, Consorcio Minero del Peru S.S., Mazca, Peru.

WEBSTER F. STICKNEY, graduate assistant, geology department, University of Tennessee, is geologist, American Zinc Co., Mascot, Tenn. He is working on surface exploration.

ROBERT H. ASHLOCK, mining geologist, New Jersey Zinz., Ely, Nev., is now with U. S. Smelting Refining & Mining Co., Salt Lake City.

JOHN J. REIFF, chief geologist, Lone Star Steel Co., Lone Star, Texas, has joined H. & H. Exploration, Grand Junction, Colo.

ALFRED LLOYD PENHALD, president Asbestos Corp. Ltd., Thetford Mines, Quebec, has been elected president for 1955 to 1956 of the Canadian Institute of Mining and Metallurgy.

JOHN B. FORD, mining geologist, has opened an office in Riverton, Wyo. Mr. Ford was geologist, Pickands, Mather & Co., Crystal Falls, Mich.

DONALD H. BAILEY is geologist with the International Nickel Co. of Canada Ltd., Creighton Mine, Ont.

JOHN A. BROWN, chief geologist, Minnesota Mining & Manufacturing Co., St. Paul, will head the new geology department. Mr. Brown joined the company in 1933 and has been chief geologist since 1945.

GORDON J. WILLIAMS, geologist, and dean of the College of Mining, University of Otago, Dunedin, New Zealand, is in the U. S. for six months studying mining processes.

GEORGE TOWER, manager, South American mining interest of Mauricio Hochschild & Co., has resigned because of health, but will continue in a consulting capacity. C. L. SPENCER, formerly with the Hochschild interests in Chile, succeeds Mr. Tower.

ROBERT L. MEYER, mining engineer and geologist, has returned to San Francisco, Calif., after several months of exploration work in South America.

KEITH MARTIN, geologist, Chino Mines Div., Kennecott Copper Corp., has joined Bear Creek Mining Co., Tucson, Ariz., as assistant geologist.

ROYAL S. FOOTE, head of the Geophysical Exploration Branch, Raw Material Division, U. S. Atomic Energy Commission since 1953, has resigned to form Resources Development Corp., uranium and mining consultants and specialists.

RONALD T. MCMILLAN has resigned as geologist for the Fresnillo Co., Fresnillo, Zacatecas, Mexico, to accept a position as geologist with the American Metals Co., Ltd., Denver, Colo.

GEORGE D. WINANS, former mining engineer and shift boss, Banner Mining Co., Tucson, Arizona, has opened a private practice in mining engineering in Tucson.

MERLE H. GUISE, who had been visiting various mining areas in Australia, left for a tour through Indonesia, and the tin dredging areas in Malaya.

JOHN A. ALLAN, 70, former head of the University of Alberta geology department, died in Edmonton, Alberta, late in May. He helped establish the Alberta geological survey.

GEORGE E. APPS is now with the Geology Department, Granby Consolidated M .S. & P. Company, Ltd., Copper Mountain, B. C.

EVERETT J. LEES has been appointed Geologist in Charge, Aquaries Operation, Pardee Amalgamated Mines, Ltd., Algoma Mills, Ontario.

JOHN G. BARRY, former chief mining geologist, American Smelting and Refining Co., has been named staff engineer, Exploration Division, Atomic Energy Commission, succeeding DAVID D. BAKER, now deputy director of the Mining Division.

JOHN CROSTON, mining engineer for the General Services Administration, has returned to Washington from a visit to the Nicaro nickel plant in Cuba, and bauxite mining operations in Jamaica, Haiti, and the Dominican Republic.

P. J. SHENON and R. P. FULL, mining geologists of Salt Lake City, have established a branch office of their firm in Grand Junction, Colorado. The office, which is located in the Munro-Morrison Building, will be in charge of A. L. PAYNE. Mr. Payne was associated with Shenon and Full for two years in Cuba and previously had been with American Smelting and Refining Company in South America and Southwestern United States. He has recently completed requirements for a Ph.D. at Stanford.

A. H. WADSWORTH, JR., of the Wadsworth Exploration Company of Bay City, Texas, and K. D. KAASCH, of the Climax Molybdenum Company of San Antonio, Texas, spoke on "Gulf Coast Uranium" to the Houston Geological Society on May 2nd; to the Corpus Christi Geological Society on May 6th; to the McAllen Chapter of the A.P.I. on June 14th; and to the South Texas Society of Geophysicists on July 13th in San Antonio, Texas.

PIERRE ROUTHIER is now Maître de Conférences, in: "Laboratoire de Géologie Appliquée—Faculté des Sciences de Paris." He is developing the teaching of field geology and conducted this year "field schools" in the Jura, Pyrénées and Corsica.

J. W. PEOPLES will be on leave from Wesleyan College for two years and will be in the Philippine Islands. E. P. LEHMANN will be Acting Chairman, Department of Geology, Wesleyan University, Middletown, Connecticut. The address of J. W. Peoples and family after July 1, 1955, will be Care U. S. Geological Survey, APO 928, San Francisco, California (c/o Postmaster).

ALLEN F. AGNEW has accepted a position as Associate Professor of Geology at the University of South Dakota in Vermillion, beginning in September 1955. He has been project chief of the Wisconsin and Iowa zinc-lead projects in Platteville, Wis., for the U. S. Geological Survey.

PAUL H. KNOWLES has returned to the United States after examining several radioactive deposits in Northern Chile. He has accepted an appointment as Geologist with the Explorations Branch of The Atomic Energy Commission in Grand Junction, Colorado.

CHARLES F. DAVIDSON has resigned from the post of Chief Geologist of the British Atomic Energy Division, terminating 21 years' service with the U. K. Geological Survey, to accept the Professorship of Geology in the University of St. Andrews, Scotland.

ARTHUR BEVAN, Principal Geologist of the Illinois State Geological Survey since 1947, has retired in order to resume field studies in the Appalachians of west-central Virginia. Before returning to the Illinois Survey, he had been State Geologist of Virginia for 18 years. He will reside northwest of Staunton at the western edge of Shenandoah Valley. The address is Churchville, Virginia.

EDWARD L. CLARK has resigned as State Geologist of Missouri and ex-officio member of the Missouri State Highway Commission to become vice president and a member of the board of directors of the Four Corners Uranium Corporation, with offices in Grand Junction, Colorado. He is also a board member of the Moreno Oil and Uranium Corporation of Colorado. THOMAS R. BEVERIDGE has been appointed State Geologist and ex-officio member of the Commission for a four-year term beginning July 1, 1955.

ROBERT M. DREYER has been appointed Chief Geologist of the Kaiser Aluminum and Chemical Corp., Oakland, California.

EDWARD WISSER and MANNING W. COX announce their association as the firm of Wisser and Cox, consulting geologists, at 55 New Montgomery Street, San Francisco.

KENNETH E. FIELDS, General Manager of the Atomic Energy Commission, announced the establishment of a Division of Civilian Application in the AEC staff, and the appointment of HAROLD L. PRICE as Director. The new Division takes the place and assumes the responsibilities of the Division of Licensing and carries out other civilian use activities contemplated by the Atomic Energy Act of 1954 which encourages "widespread participation in the development and utilization of atomic energy for peaceful purposes."

THE SOCIETY OF EXPLORATION GEOPHYSICS announces the following elections: R. C. Dunlap, Jr., Dallas, was elected president; Dave P. Carlton, Houston, vice-president; George A. Grimm, Midland, Texas, secretary-treasurer; Dr. Norman Ricker, Tulsa, editor. The new members of the SEG executive committee will take office at the close of the society's 25th annual meeting, October 6, 1955, in Denver, Colorado.

THE FOURTH NATIONAL CLAY CONFERENCE sponsored by the Clay Minerals Committee of the National Research Council was held at The Pennsylvania State University, October 10–13. The following topics were given particular emphasis: mixed-layer clays; thermal transformations; and clay water systems. A number of prominent scientists from abroad were invited to attend and gave reports on the status of clay mineral investigation in their respective countries.

AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS, Western Canada Regional Meeting and ALBERTA SOCIETY OF PETROLEUM GEOLOGISTS, 5th Annual Field Conference, was held on September 14–17, at the Jasper Park Lodge. Symposia on the Jurassic and Carboniferous Systems of Alberta and adjacent areas were presented September 15th and 16th, with informal discussions each evening. On September 17th, participants saw excellent geologic sections from Cambrian to Cretaceous including typical well-developed Rocky Mountain structures.

THE NEW MEXICO GEOLOGICAL SOCIETY, in conjunction with the Roswell Geological Society, will hold its Sixth Annual Field Conference in South-Central New Mexico on November 11, 12, and 13, 1955. Truth or Consequences, New Mexico will be headquarters. The Conference will examine: (1) the Paleozoic section of the San Andres Mountains under the leadership of Dr. Frank Kottlowski; (2) the structure and stratigraphy of the Iron Mountain mining district, Cuchillo Mountains, under the leadership of Dr. Richard A. Jahns and Dr. Clay T. Smith; (3) the complete section from Precambrian to Tertiary in the Caballo Mountains, under the guidance of Dr. Vincent Kelley, Caswell Silver and Hugh Bushnell. Information may be obtained from Frank W. Podpechan, Box 899, Roswell, New Mexico.

THE UNITED STATES ATOMIC ENERGY COMMISSION announced a value for enriched uranium leased for research reactors and sale prices for normal uranium and heavy water which should be of assistance to those nations planning to use research reactors as part of their program for benign uses of the atom. The value established for lease of uranium enriched to 20 percent in U-235 for use in research reactors under the bilateral agreements between the United States and friendly nations is $25 per gram of contained U-235; for heavy water—$28 per pound; for normal uranium metal—$40 per kilogram.

The AAPG Nominating Committee has submitted its nominations for officers of the Association for next year. For President: Carey Croneis of Rice Institute and Theodore A. Link, of Link, Downing, and Cooke, Ltd. For Vice-President: Ben H. Parker, Frontier Refining Co., Denver, and Walter H. Spears, Union Producing Company, Shreveport, Louisiana. For Secretary-Treasurer: W. A. Waldschmidt, Consultant, Midland, Texas. For Editor: W. D. Krumbein, Northwestern University.

CORRECTION: An error occurred in the paper by John S. Brown, J. A. Emery, and P. A. Meyer, Jr., in Vol. 49, No. 8, p. 899, in the table listing percent U; sample No. 2 should read .001 instead of .024.